Relativity

Outline

- Special relativity
  - What is special relativity about?
  - The evolution of concepts of space and time through history
  - Newtonian mechanics and Maxwell's equations
  - Einstein's space-time and consequences of Einstein's theory
  - Special relativity "paradoxes"
- General relativity
  - What is general relativity about?
  - "The happiest thought of my life"
  - Light and time in gravitational fields
  - Gravity as curvature of spacetime
  - The frontier of current theoretical research: gravity and quantum mechanics
- Conclusions and further reading suggestions

What is relativity about?

- There are actually two kinds of relativity theories: special and general, both created by **Einstein**.

➢ **Let's start with special relativity.**

- Here at Fermilab, we accelerate particles to very nearly the speed of light, and the way things move at such high speeds is very different from what we are used to in everyday life.

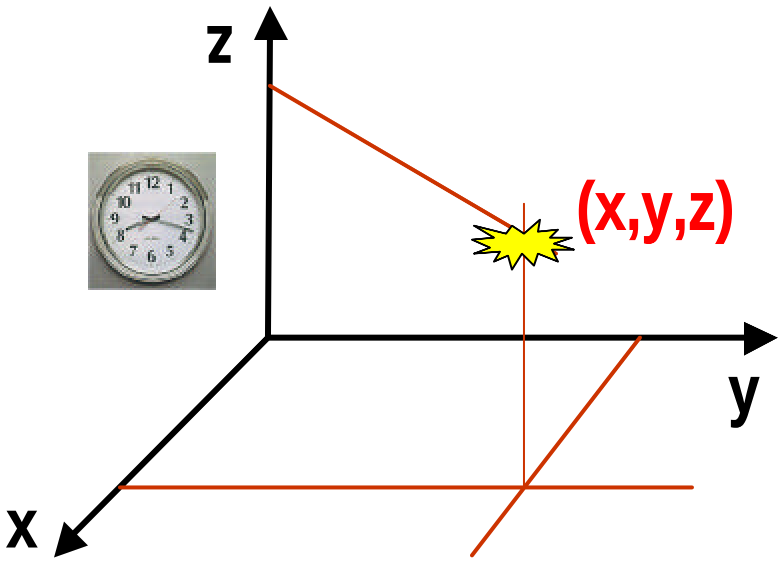
1. Special relativity allows us to describe what happens at very high energies
2. ***Fundamentally, though, both special and general theories of relativity deal with the concepts of space and time***

- It is curious to see how the understanding of space and time evolved through history…

What is space and time, really?

- Einstein said in his "Relativity":

…In the first place we entirely shun the vague word "space", of which, we must honestly acknowledge, we cannot form the slightest conception, and we replace it by "motion relative to a practically rigid body of reference".

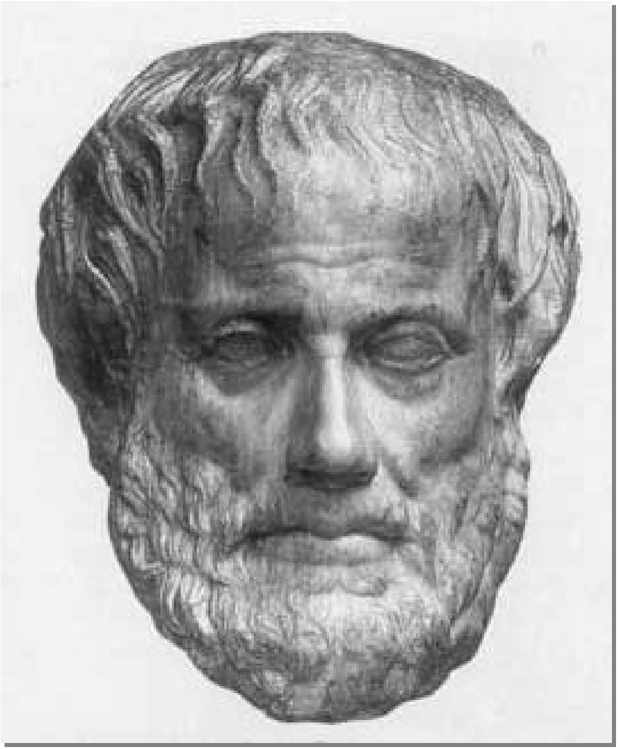


- Replace "rigid body of reference" with three long rods at 90º to each other.

- The position of an object is determine by the distance along each of them.

➡ This set of rods + clock is called **a reference frame**

Aristotle's physics

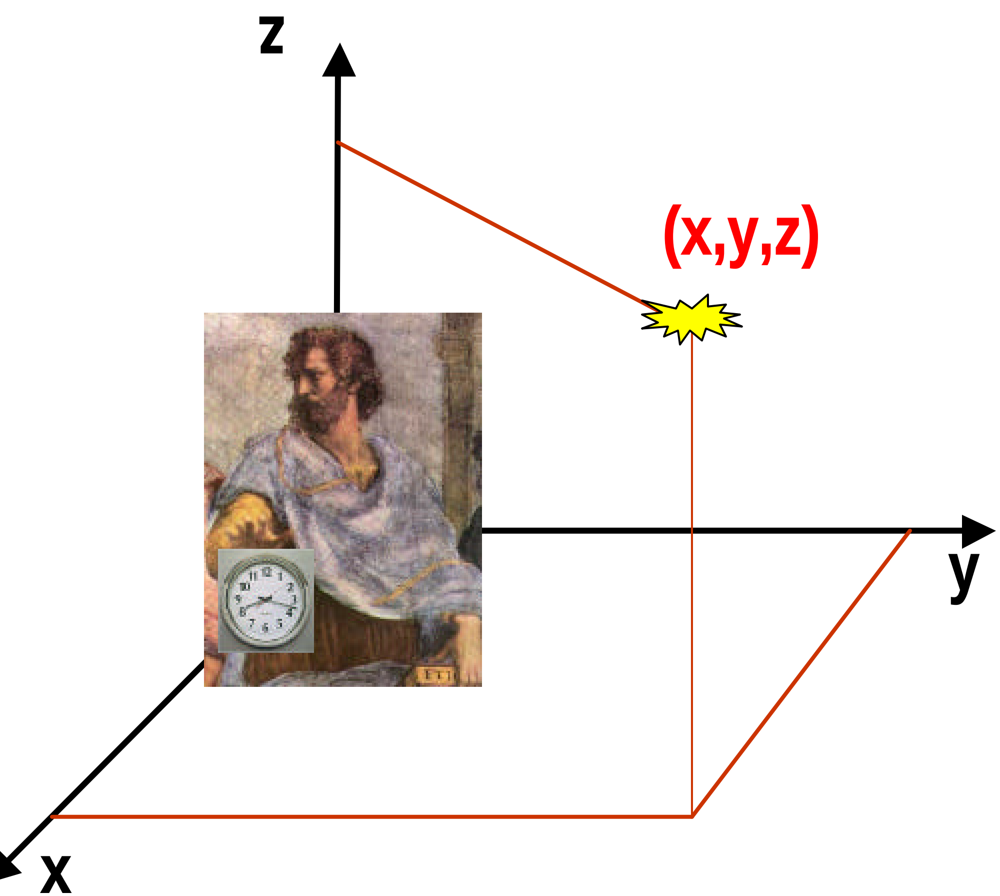


Aristotle
384-322 B.C.

- Aristotle's views on space, time, and motion were very intuitive; they are pretty much how people "feel" about these things.

- Here are Aristotle's views on space and time:
  - *Every sensible body is by its nature somewhere.* (Physics,Book 3, 205a:10)
  - *Time is the numeration of continuous movement.* (Physics, Book 4, 223b:1)

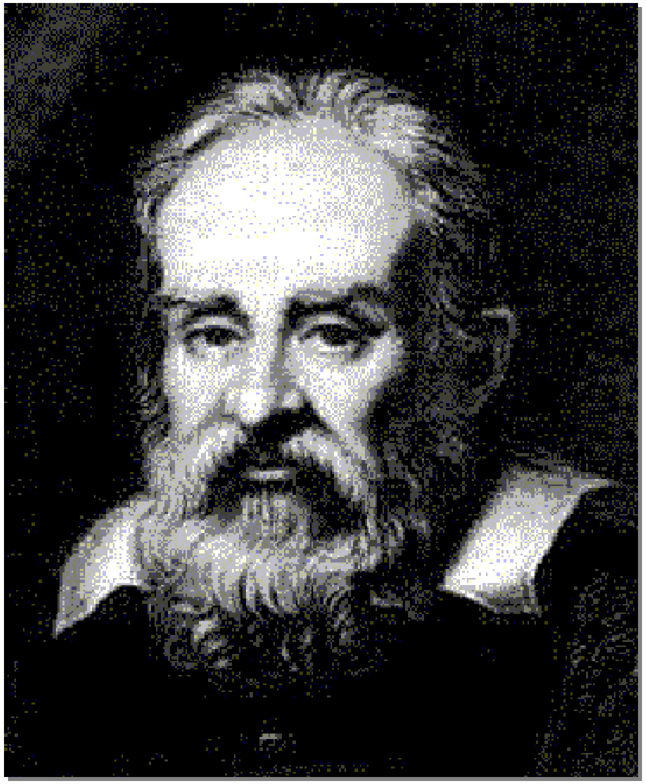
Aristotle's space and time



- There exists a Prime Mover, a privileged being in the state of Absolute Rest
- The position of everything else is measured with three numbers (x, y, z) with respect to the Prime Mover, who sits at (0,0,0).
- The time is measured by looking at the Prime Mover's clock

This point of view prevailed for almost 2,000 years

Galileo's challenge



Galileo Galilei
1564 -1642

- Galileo argued that there is no such thing as "Absolute Rest". In his view:
- The mechanical laws of physics are the same for every observer moving with a constant speed along a straight line
  - this is called "inertial observer" for short.

Galileo's Parable of the Ship

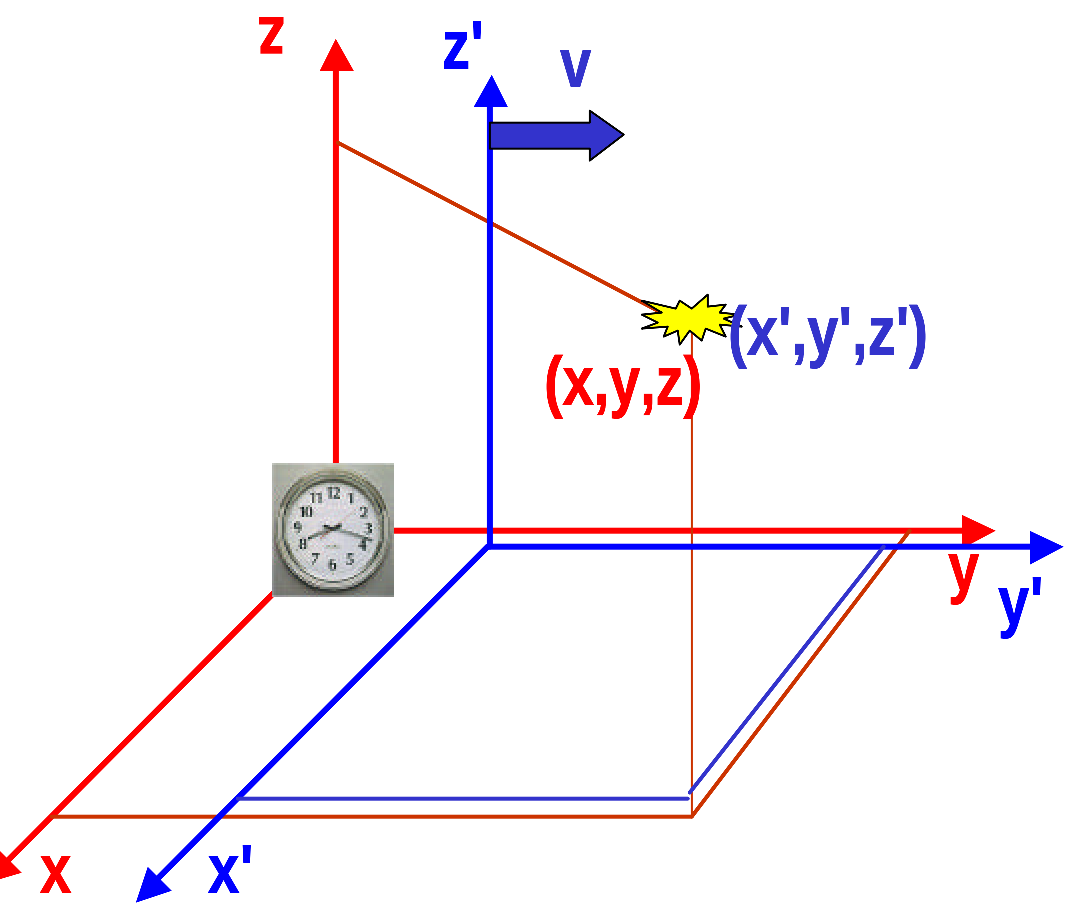
"Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it.

With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need to throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction.

When you have observed all of these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that.

You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.... "

Galileo's space and time

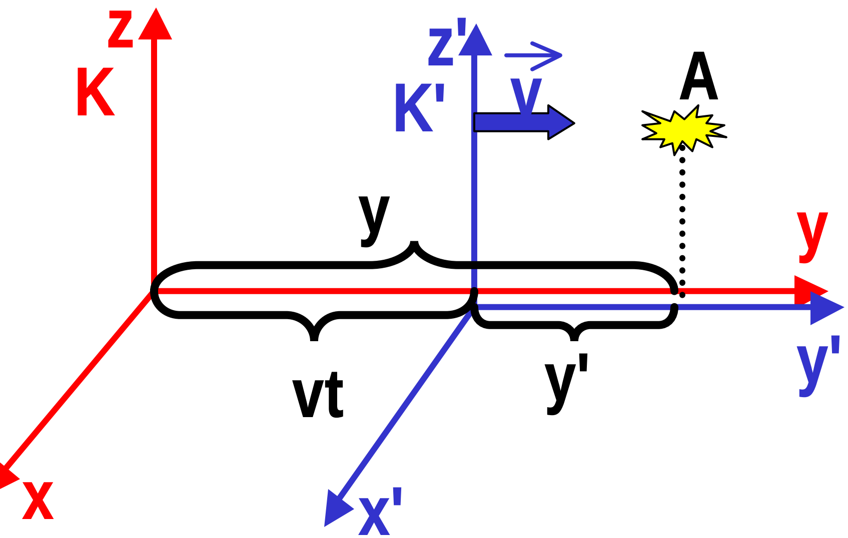


- Every inertial observer could declare themselves "the Prime Mover", and measure the position of everything with respect to their own set of (x, y, z)

- BUT ! The time is still measured by looking at the Prime Mover's clock!

➡ Galileo finished off the concept of Absolute Space, but not that of Absolute Time.

Galileo's transformations



- We have two frames of reference, K and K', and K' is moving along axis y with some constant speed v.
- Something happened at point **A**.
- According to Galileo, there is no one special reference frame -- if we know where A happened in one frame, we are done! That's because:

$$y = y' + vt$$
$$x = x'$$
$$z = z'$$
$$t = t'$$

Galileo transformations:
know what happened in one frame, can tell what happened in another

Addition of velocities

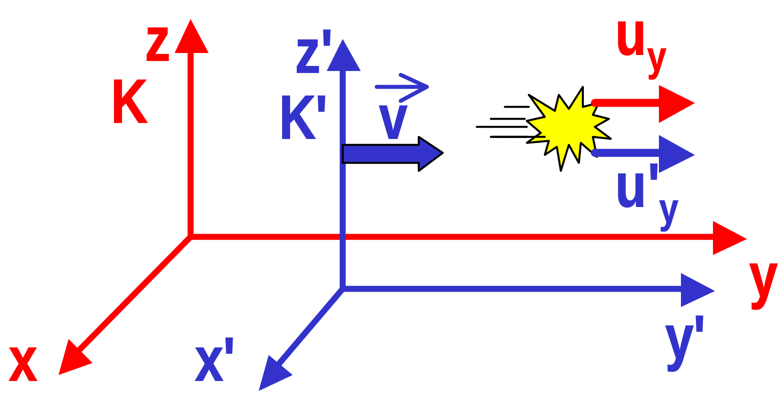
- We know how positions of an object transform when we go from one inertial frame of reference to another (Galileo transformations)

$$y = y' + vt$$
$$x = x';\ z = z';\ t = t'$$

- What about velocities?

$$u_y \equiv \frac{\Delta y}{\Delta t} = \frac{\Delta(y' + vt)}{\Delta t} = \frac{\Delta y'}{\Delta t} + \frac{\Delta(vt)}{\Delta t} \equiv u_y' + v$$
$$u_x = u_x';\ u_z = u_z'$$

velocity of an object in K is equal to its velocity in K', plus the velocity of K' with respect to K



Newton's laws of mechanics

Sir Isaac Newton
1642-1727

- Newton's laws of mechanics are in agreement with Galileo's relativity
  1. A body, not acted upon by any force, stays at rest or remains in uniform motion, whichever it was doing to begin with
  2. To get an object to change its velocity, we need a force

Force = mass x acceleration

(acceleration = change in velocity)

$$\vec{F} = m\vec{a} \equiv m\frac{\Delta\vec{v}}{\Delta t}$$

Newton's laws are the same in all inertial frames

- From our law of addition of velocities (which followed from Galileo transformations):

$$\boxed{u_y = u_y' + v}$$

velocity of an object in K is equal to its velocity in K', plus the velocity of K' with respect to K

we can derive what will happen to acceleration:

= 0 as v = const

$$\boxed{a_y \equiv \frac{\Delta u_y}{\Delta t} = \frac{\Delta(u_y' + v)}{\Delta t} = \frac{\Delta u_y'}{\Delta t} + \frac{\Delta v}{\Delta t} \equiv a_y'}$$

➡ **Accelerations are the same in both K and K' frames!**

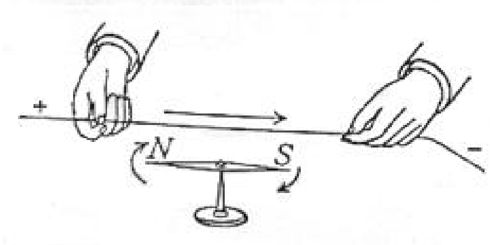
➡ So Newtonian forces (F = ma) will be the same in both frames

The clouds start to gather…

- For more than two centuries after its inception, the Newtonian view of the world ruled supreme
- However, at the end of the 19th century problems started to appear!
- Some of the end-19th century hot topics to work on included:
  - What is light? How and in what medium does it propagate?
  - Why are the equations describing electricity and magnetism inconsistent with Newton's laws?
  - The orbit of Mercury, predicted very accurately with Newton's equations, presented a small but disturbing discrepancy between predictions and observations. Why?
  - …

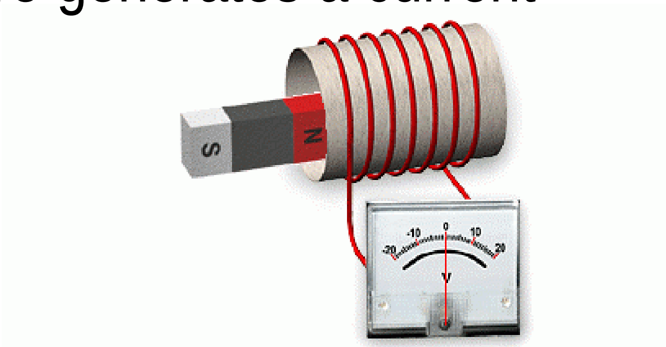
Electricity and Magnetism

- Around 1870, Orsted noted that current in a wire deflected a compass needle.



➡ Moving charges generate magnetic effects!

- Faraday observed that a magnet moving in a coil of wire generates a current



➡ Moving magnets generate currents!

Maxwell brings it all together

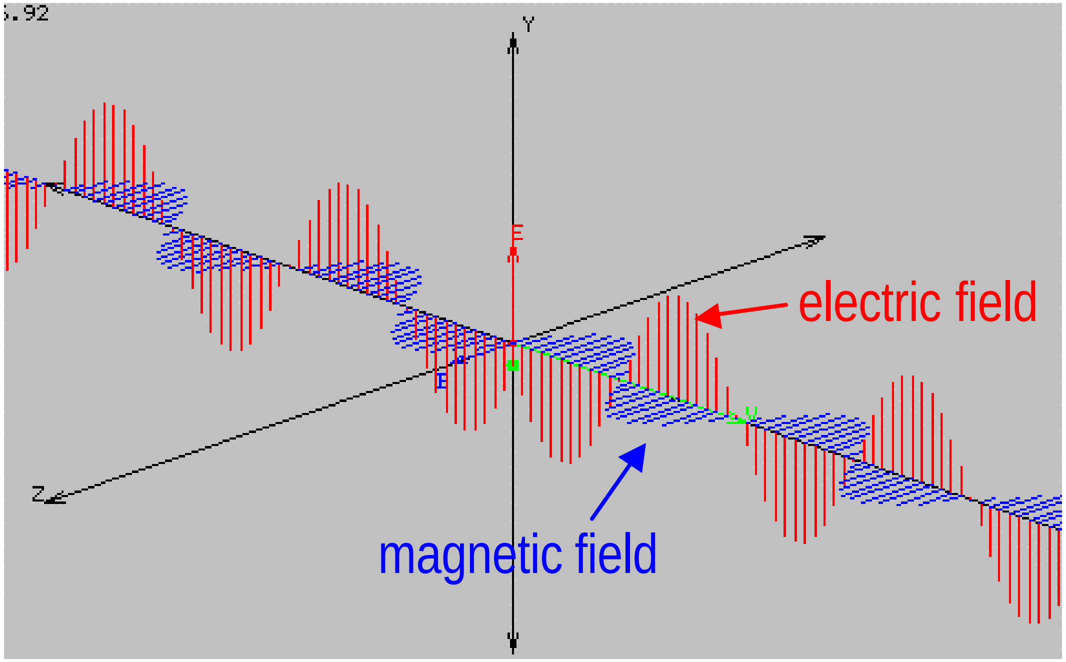
James C. Maxwell
1831-1879

- Maxwell brought together the knowledge of electricity and magnetism known in his day in a set of four elegant equations known as **Maxwell's equations**
- These equations:
  - Describe all electromagnetic phenomena with perfect accuracy to very small distances
  - They are inconsistent with Newtonian mechanics
  - **There are solutions of the equations which describe waves traveling at speed *c* = 299,792 km/s (which is also the speed of light!)**

Light = electromagnetic waves

- Maxwell himself said of the last conclusion:

We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.



➡ Light, electricity and magnetism are different aspects of the same set of phenomena!

c with respect to what?

- Maxwell's equations introduce the speed of light, *c*
  - But they don't say with respect to what this velocity is to be measured!

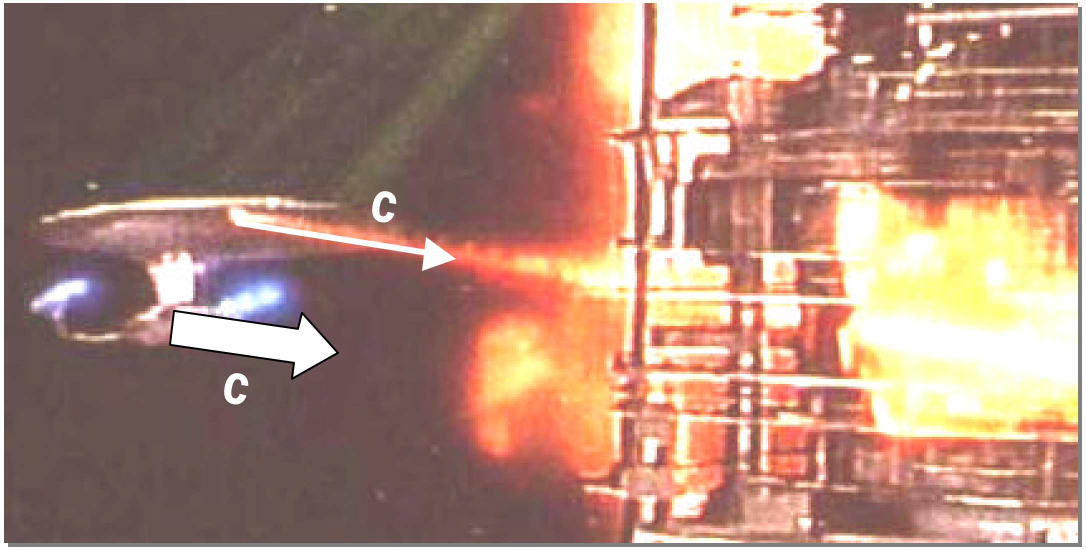
- Let's assume that we can refer the process of the propagation of light to a rigid coordinate system, as usual, and consider the propagation of light as we would any other mechanical process.

Houston, we've got a problem…

- If electromagnetism is governed by the same rules as Newtonian mechanics, the “addition of velocities” rule should also apply.

$$u_y = u_y' + v$$

But what if $u_y' = c$ and $v = c$?



- So if USS Enterprise is moving towards the Borg cube with the speed of light, *c*, and fires a photon torpedo (moving with speed *c*), the Borg should see the torpedo flying towards them with the speed of **2*c***?

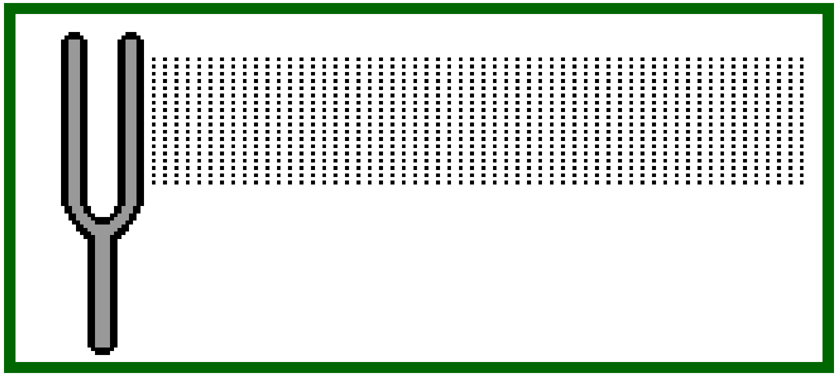
That can't be right!

- According to the principle of relativity, like every other general law of nature, the law of transmission of light in vacuum must be the same for all observers.

- Note that we said **in vacuum** -- but maybe there's a special medium that we can measure the speed of light with respect to?
  - E.g., we measure the speed of sound through air relative to air.
  - **This was not such a bad idea -- after all, light is a wave, and waves typically need something to propagate in!**

Waves in general

- The waves we are all familiar with require **something to propagate in**



Sound waves are compressions of air (water, etc.)

Spring compressions in a slinky

- What about light?
  - The most natural assumption would be that it requires a medium, too!

Ether

- This mysterious medium for light was called **ether**
- What would its properties be?
  - We see light from distant starts, so ether must permeate the whole universe
  - As Earth moves through it, there must be a kind of "ether wind" present on the surface
  - Must be very tenuous, or else the friction would have stopped the Earth long ago

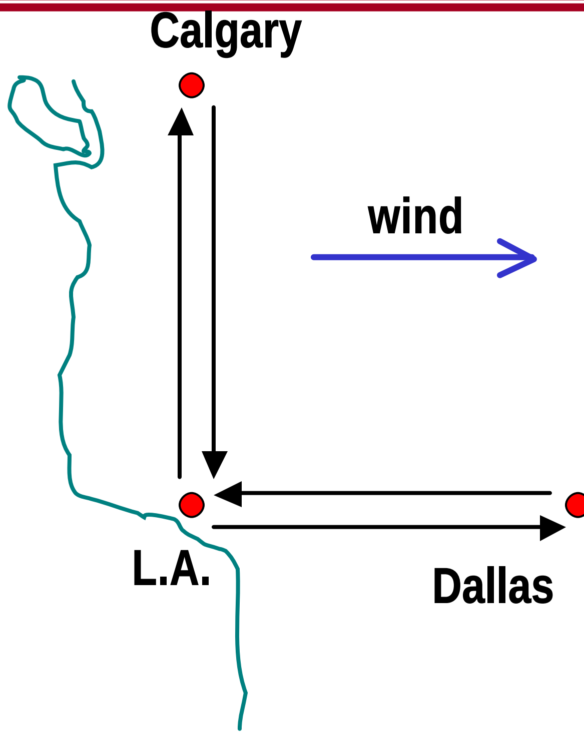
Ether would be like a ghostly wind blowing through the Universe!

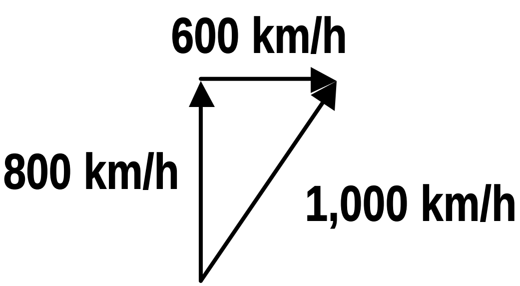
- Michelson and Morley attempted to detect ether by measuring the speed of light in two different directions: “upwind” and “downwind” with respect to ether.

Michelson's experiment: an analogy

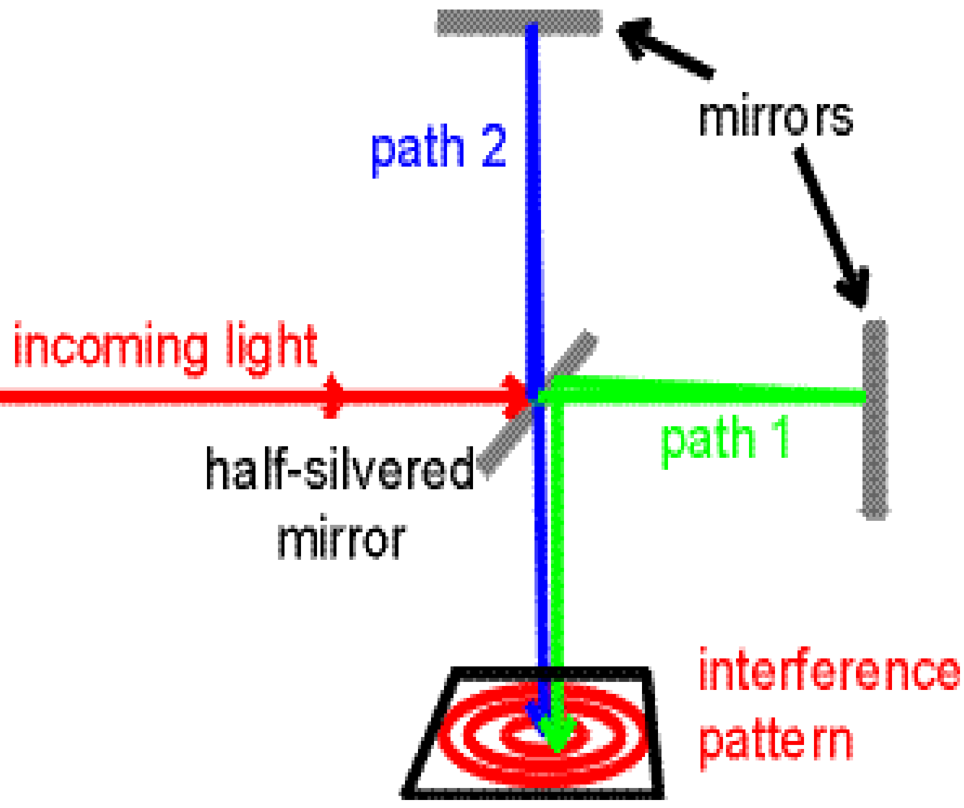
Consider the following situation:

- Two planes leave L.A. and fly one north and one east at the same speed, 1,000 km/h. They then return to L.A.
- The wind is blowing east at 600 km/h, so, relative to the ground:
  - The speed of plane from L.A. to Dallas = 1,600 km/h
    - Suppose this trip takes 1 hour.
  - The speed of plane from Dallas to L.A. = 400 km/h
    - **Overall, it will take 5 hours to get to Dallas and back**
  - The speed of plane from L.A. to Calgary = 800 km/h
  - The speed of plane from Calgary to L.A. = 800 km/h
    - **Overall, it will take 4 hours to get to Calgary and back**
- From the ratio of travel time, 4:5, the airport dispatcher concludes that there was a wind blowing and can work out the ratio of wind speed to plane speed,3:5





Michelson-Morley experiment



- Now replace two airplanes with two light beams, and wind with ether, and that will be Michelson and Morley's experiment
- Michelson and Morley used a very sensitive interferometer to detect the difference in the speed of light depending on the direction in which it travels.
- **NO such dependence was found! Speed of light was the same in both cases.**

⇨ **So NO ether?**

What do we know so far?

- Newton's mechanics based on Galileo's relativity
  - The law of addition of velocities applies.

- Maxwell's electromagnetism
  - There is a fundamental constant of nature, the speed of light (***c***) that is the same in all reference frames. The law of addition of velocities does not work for it!

Mechanics was inconsistent with electromagnetism!

Einstein's choices

- Einstein was faced with the following choices:
  - Maxwell's equations are wrong. The right ones would be consistent with Galileo's relativity
    - That's unlikely. Maxwell's theory has been so well confirmed by numerous experiments!
  - Galileo's relativity was wrong when applied to electromagnetic phenomena. There was a special reference frame for light.
    - This was more likely, but it assumed light was like any other waves and required a medium (ether) for propagation. Ether was not found!
  - There is a relativity principle for both mechanical and electromagnetic phenomena, but it's not Galileo's relativity.

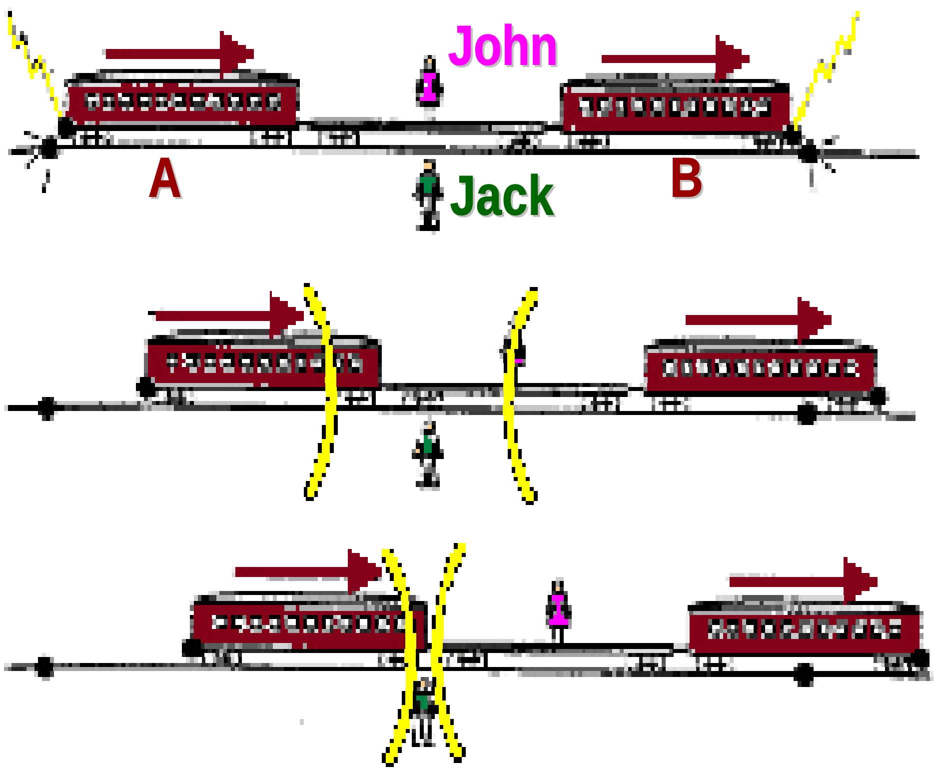
Einstein's relativity postulates

Albert Einstein
1879-1955

- It required the genius and the courage of Einstein to accept the third alternative. His special relativity is based on two postulates:
- **All laws of nature are the same in all inertial frames**
  - This is really Galileo's relativity
- **The speed of light is independent of the motion of its source**
  - This simple statement requires a truly radical re-thinking about the nature of space and time!

What's so radical about it?

- It was Galileo who finished off the concept of Absolute Space.
- **Einstein added that there is no Absolute Time, either.**
  - Simultaneity is relative!

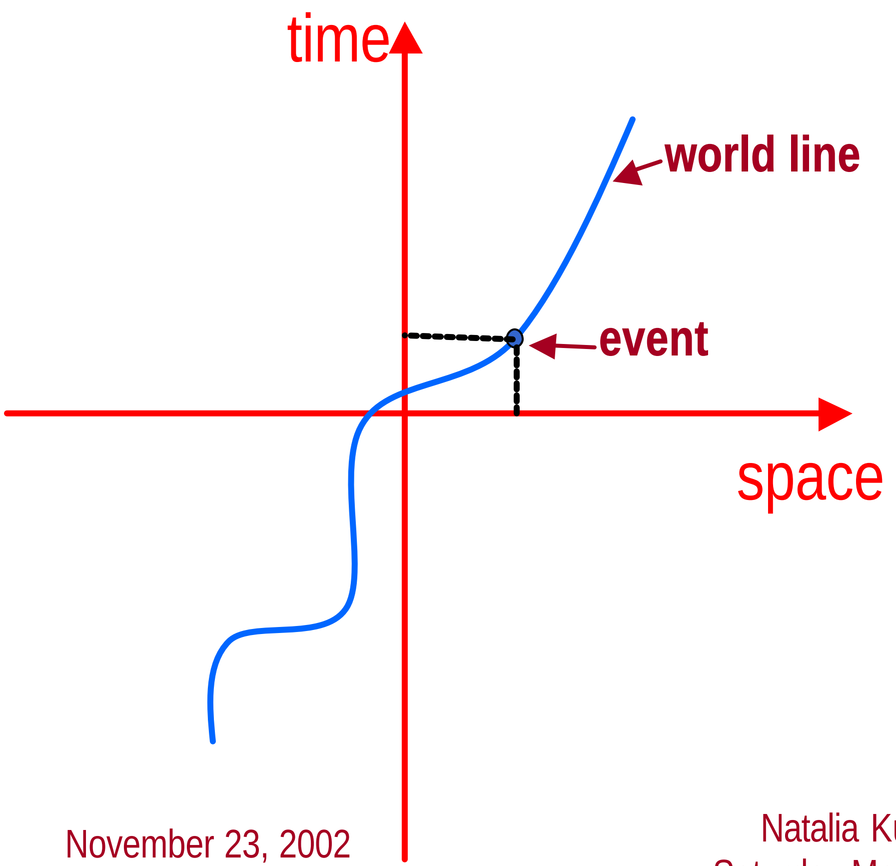


1. From the point of view of Jack, lightning struck both train cars at the same time

2. From the point of view of John, lightning struck first car A and then car B

Space-time

- There are no such things as "space" and "time", there is only four-dimensional space-time! You must always specify both space and time of an event.
- How does one visualize such a thing?

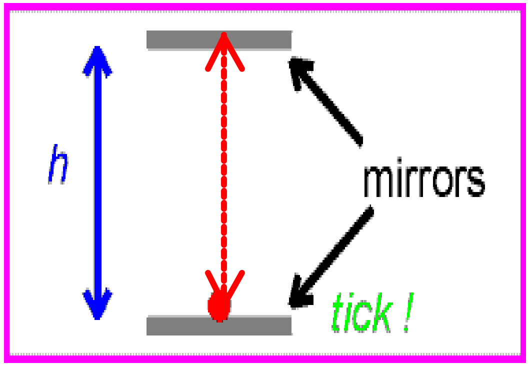


- It's hard, so people usually imagine a three-dimensional "space" with one coordinate being the time coordinate
  - this is called a **space-time diagram**

Some consequences: time dilation

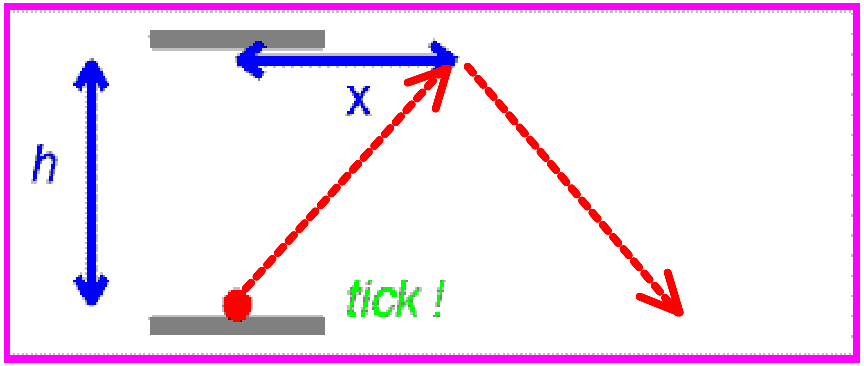
- Consider a light clock -- the time it takes for light to pass from one mirror to the other and back is one tick!

Stationary clock:



$$t_0 = \frac{h}{c}$$

Moving clock:



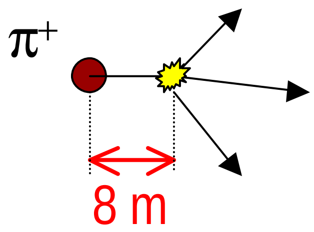
$$t = \frac{\sqrt{h^2 + x^2}}{c} = \frac{\sqrt{h^2 + (vt)^2}}{c}$$

➡ In case of moving clock, light travels a longer path between mirrors!

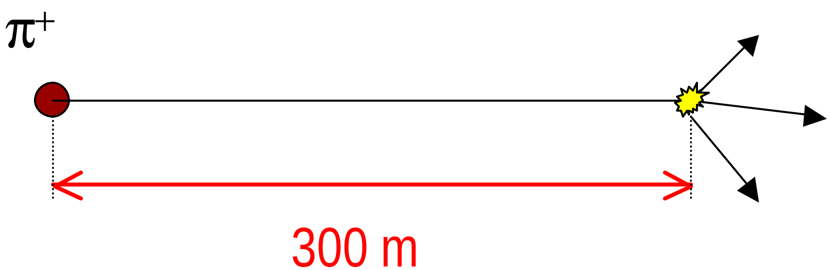
$$t = \frac{h}{c} \cdot \frac{1}{\sqrt{1 - v^2/c^2}} = t_0 \cdot \frac{1}{\sqrt{1 - v^2/c^2}}$$

➡ $t > t_0$, Moving clock ticks more slowly!

What does this mean?



No time dilation

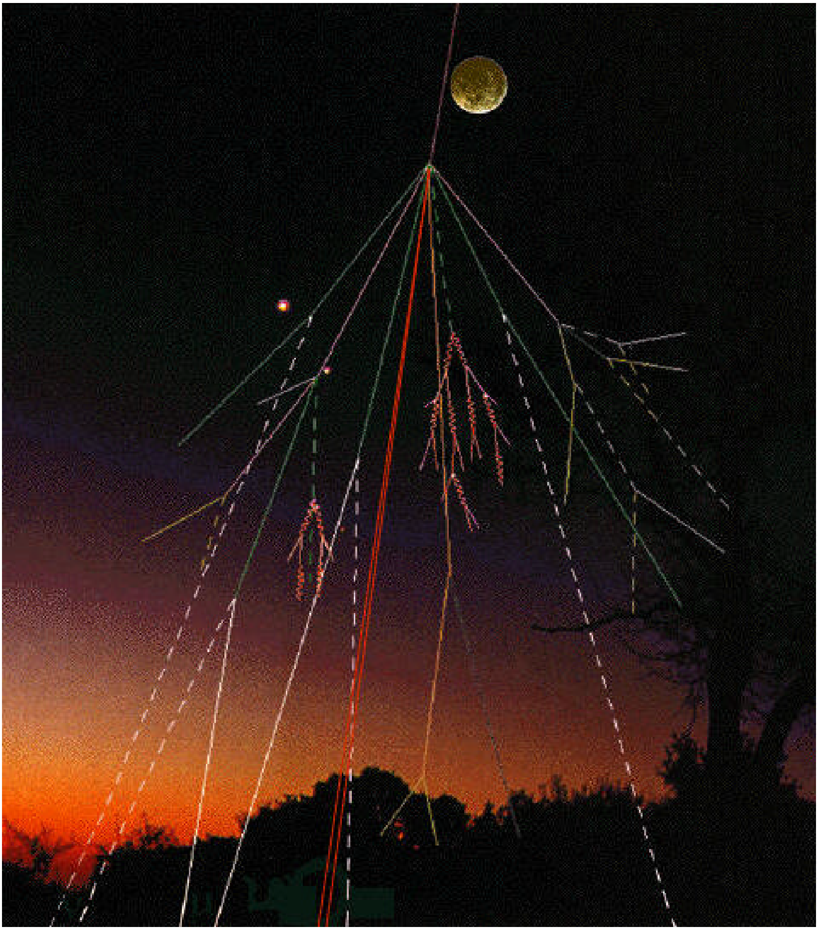


With time dilation

- **Time in a moving system slows down comparing to a stationary system!**

- E.g., charged pions have a lifetime of $t = 2.56 \times 10^{-8}$ s, so most of them would decay after traveling $ct = 8$ m.
- But we have no trouble transporting them by hundreds of meters!

Reality of time dilation: cosmic rays



- A cosmic ray is a high-speed particle originating from the Sun or from outside the solar system.
- By ground level, we are usually left with lots of muons -- particles similar to electrons, but heavier
  - They only live for about 2 microseconds
- The fraction of muons reaching the ground is an objective fact, upon which all observers must agree.

Reality of time dilation: cosmic rays (2)

- Let T = time after which half of muons in a sample of muons will decay away (half-life)
- Suppose muons travel at speed v
- For ground observer:

$$t = \frac{l}{v}$$ ⇐ **time for the muon to reach ground**

divide that by half-life of the moving muon:

$$\#muons = \frac{t}{(T/\sqrt{1-v^2/c^2})}$$ ⇐ **fraction of muons that made it**

- For observer traveling with the muon:

$$t' = \frac{l'}{v}$$ ⇐ **time to cover distance l'**

divide that by half-life of the stationary muon:

$$\#muons = \frac{t'}{T}$$ ⇐ **fraction of muons that made it**

Reality of time dilation: cosmic rays (3)

- Because both observers must agree on the fraction of muons that reached the ground, we have

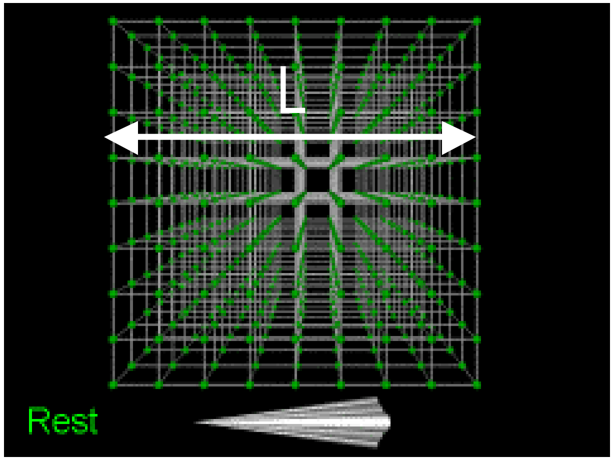
$$\#muons = \frac{t}{(T/\sqrt{1-v^2/c^2})} = \frac{l}{v \cdot T} \cdot \sqrt{1-v^2/c^2} \quad = \quad \#muons = \frac{t'}{T} = \frac{l'}{v \cdot T}$$

- Solving this, we get:

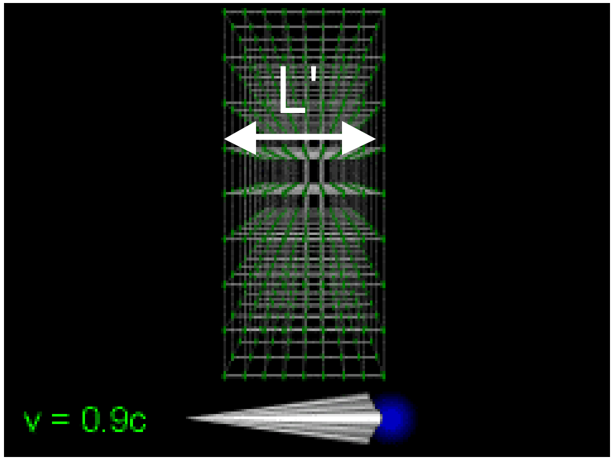
$$l' = l \cdot \sqrt{1-v^2/c^2} \Rightarrow l' < l$$

- So there must be a contraction of length along the direction of motion!
  - Time dilates, space contacts by the same factor $\sqrt{1-v^2/c^2}$

What does this mean?



- **An observer moving along an object will find it shorter than it would be if the observer was standing still!**



- So a space ship moving with 9/10 the speed of light along a lattice will find that the lattice is shorter than it was when the ship was at rest!

More consequences : addition of velocities

- Knowing now time and space behave, we can now derive how velocities transform when we go from one inertial system to another:

$$u_y \equiv \frac{\Delta y}{\Delta t} = \frac{\Delta y}{\Delta t'} \cdot \frac{\Delta t'}{\Delta t} = \frac{u_y' + v}{1 + \frac{u_y' \cdot v}{c^2}}$$

$$u_x = u_x'; u_z = u_z'$$

- It is only different from our familiar law of addition of velocities by a factor of $(1 + u_y' \cdot v/c^2)$ in the denominator, but what a difference that makes!
- If $v = c$ and $u_y' = c$, then $u_y = 2c / (1+c^2/c^2) = c$ $\Rightarrow$

Speed of light really is the same in all frames!

Lorentz transformations

$$y = \frac{y' + vt'}{\sqrt{1 - v^2/c^2}}$$

$$t = \frac{t' + (v/c^2)y'}{\sqrt{1 - v^2/c^2}}$$

$$x = x'$$

$$z = z'$$

These are Lorentz transformations

- They show how space and time are related for two different inertial observers in special relativity

- **They show that space and time really are no longer independent in relativity!**

- The same relativistic factor $1 - v^2/c^2$ governs both space contraction and time dilation
  - They are reduced to Galilean transformations when v << c

- Maxwell's equations do not change under these transformations

What remains the same?

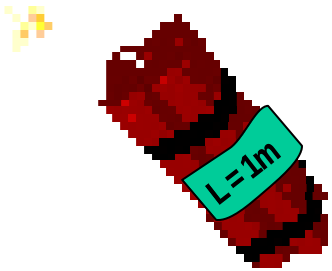
✓ Events that take place

✓ Speed of light

✓ Transverse lengths (heights, widths)

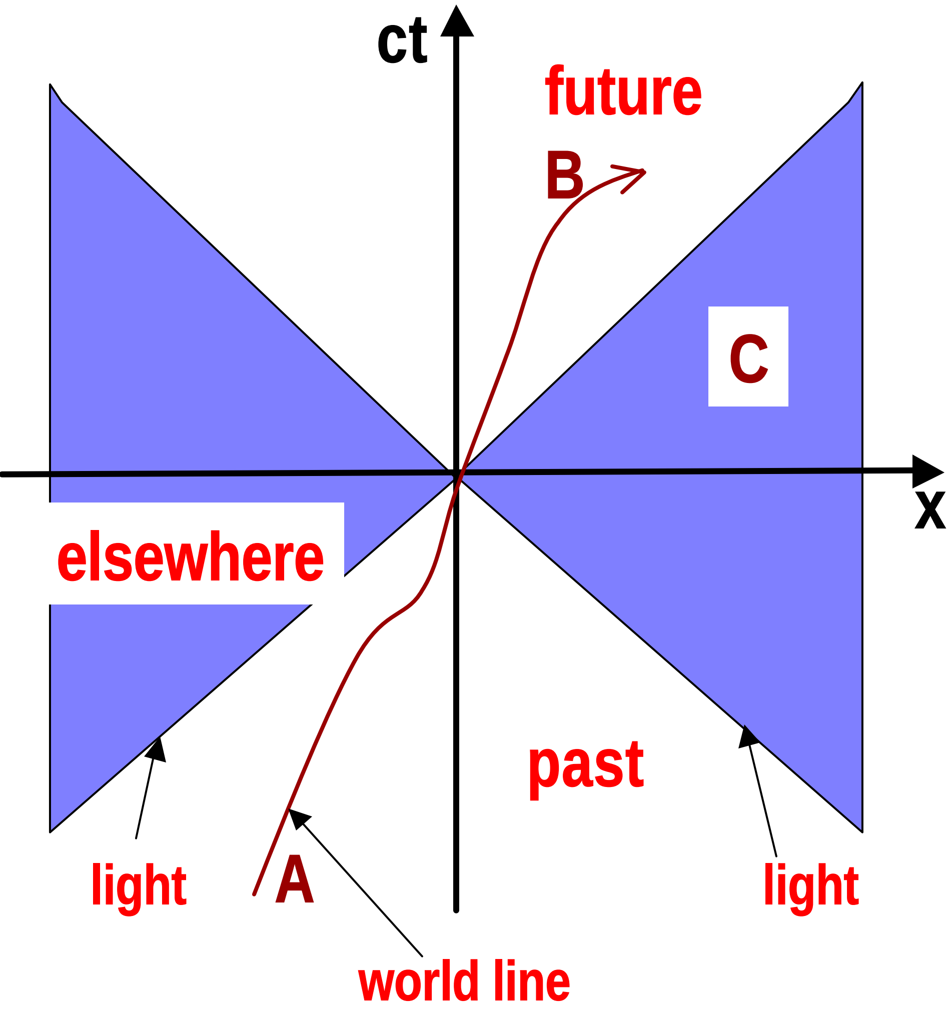
- Here's a question for you.

1. Suppose you have a pack of dynamite with some kind of length measuring device strapped to it.
2. You can send the dynamite traveling as close to the speed of light as you want
3. The device is programmed to set the dynamite off when its length becomes 1/2 of its original length



➔ At what speed will it go off?

Light cone

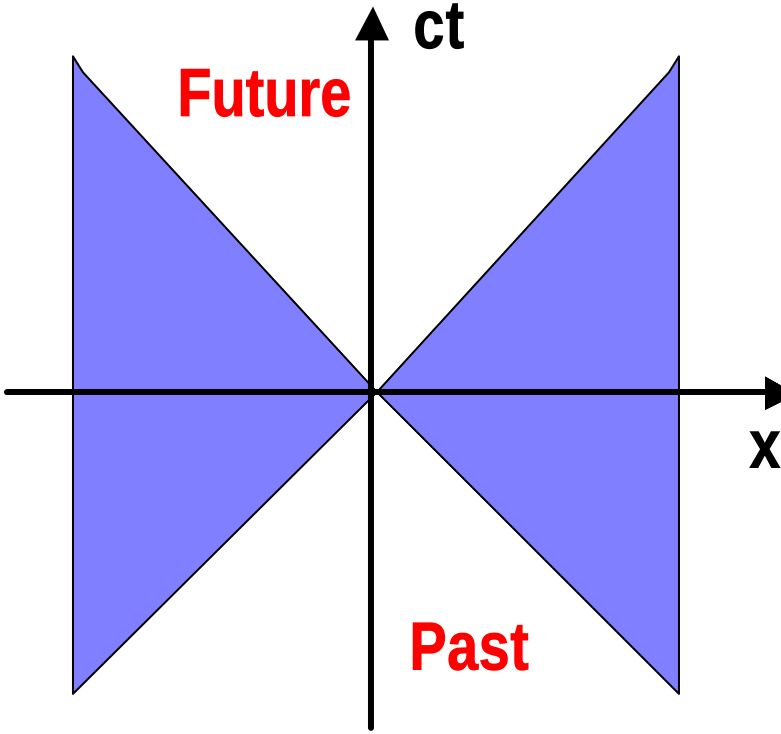


- It is very convenient to represent space-time as a diagram with one axis being space and the other, time
- Because the speed of light is the upper limit for all velocities, the space time is divided into three regions by a cone called the "light cone":
  - **Past, Future, Elsewhere**
- A path on this diagram is called a world line

Can we really never travel faster than light?

- The second postulate (that c is the same in all frames) also means that it is the highest possible speed. Otherwise, it would always be possible to come up with a reference frame where the speed of light would be higher than the "limit".

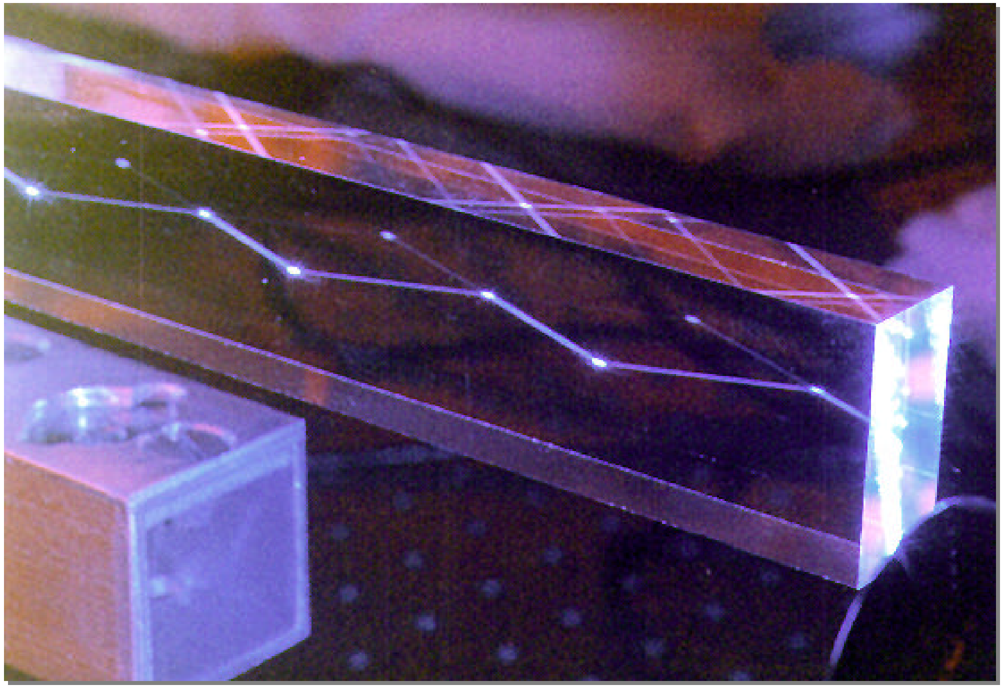
- However, people have speculated that there may exist objects that are superluminous (always traveling faster than light). They are called tachyons.
- So far, they have not been seen.
- Faster-than-light travel means traveling backwards in time would be possible, which would violate causality.



Just say NO to time travel!

Traveling faster that light: a catch!

- Notice, however, that special relativity only precludes things from traveling faster than light **in vacuum**.
- In media (e.g., water or quartz) particles can travel faster than light can in that medium.
- This results in the so-called Cherenkov radiation, which is a very beautiful phenomenon widely used by physicists



BaBar experiment's DIRC: Detector of InternallyReflected Cherenkov Radiation

Cherenkov light is similar to the sonic boom

- Sonic boom is caused by an object moving faster than sound (~750 mi/h at sea level)
- An aircraft traveling through the atmosphere continuously produces air-pressure waves similar to the water waves caused by a ship's bow.
- When the aircraft exceeds the speed of sound, these pressure waves combine and form shock waves which travel forward from the generation or "release" point.

What would you see if you were traveling close to the speed of light?

- Imagine you are a proton traveling along Fermilab's Tevatron at a speed close to the speed of light. What would you see?

- There are several effects we need to take into account:
  - Lorentz space contraction and dilation of time?
    - Yes, but these effects will be "worked into" these two effects:
  - Aberration of light
  - Doppler shift

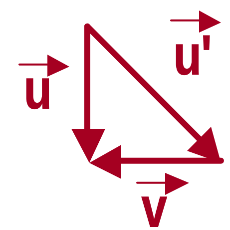
- What is aberration of light? What is Doppler shift? Let's find out!

Aberration of light

- "Aberration" is just a fancy word for "addition of velocities"
- Aberration of light can be illustrated by aberration of rain

Train stationary
Rain falling at 60 km/hour

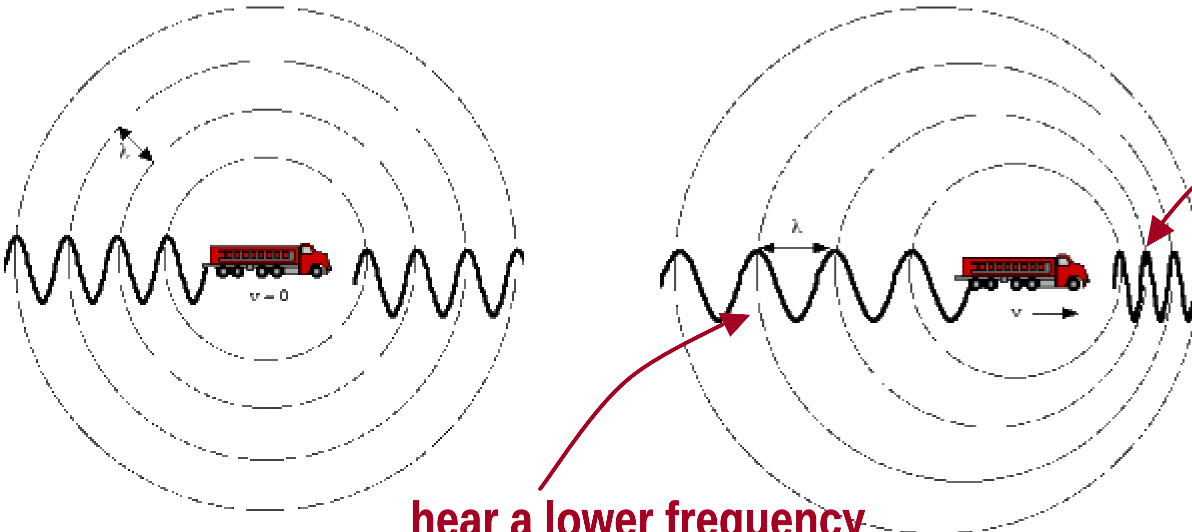
Train is moving at 60 km/hour
Rain appears to be falling at an angle



- At large velocities, we start to observe a similar phenomenon with light
  - We just need to use the relativistic formula for addition of velocities
  - **The net effect is that light appears to converge on a point directly opposite the moving observer**

Doppler effect

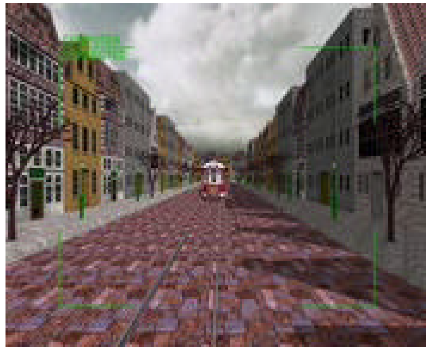
- The Doppler effect is the familiar frequency shift we've all heard when a fire truck with its siren on passes by



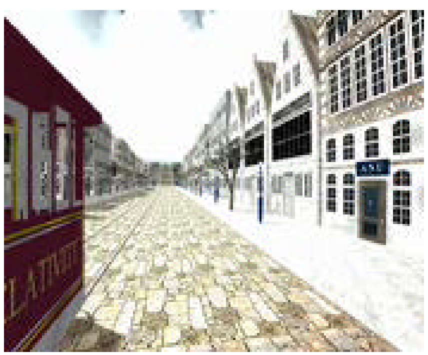
- Similarly for light, in the direction of motion it appears to have a higher frequency (*blueshifted*).

By tram

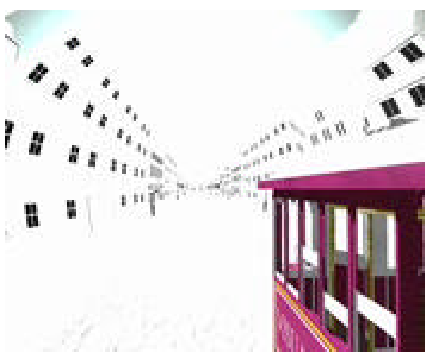
Through tram

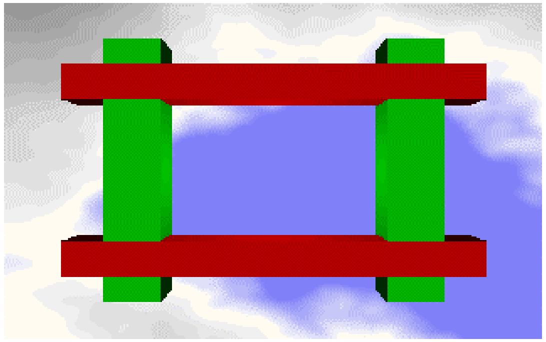


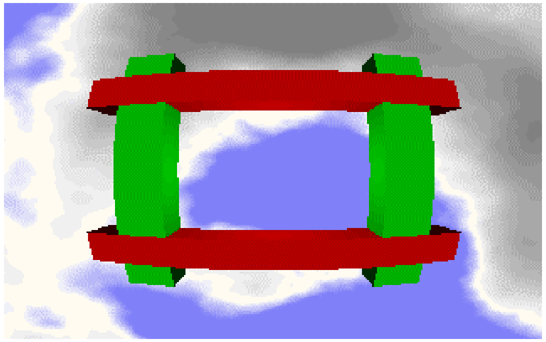
Doppler tram

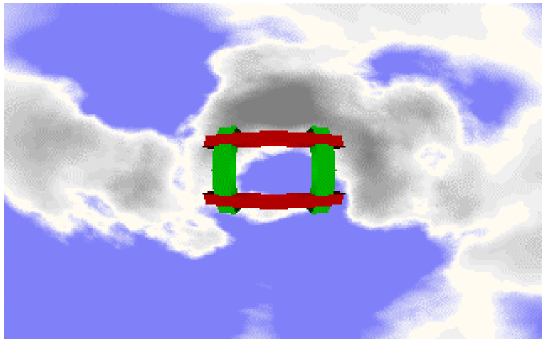


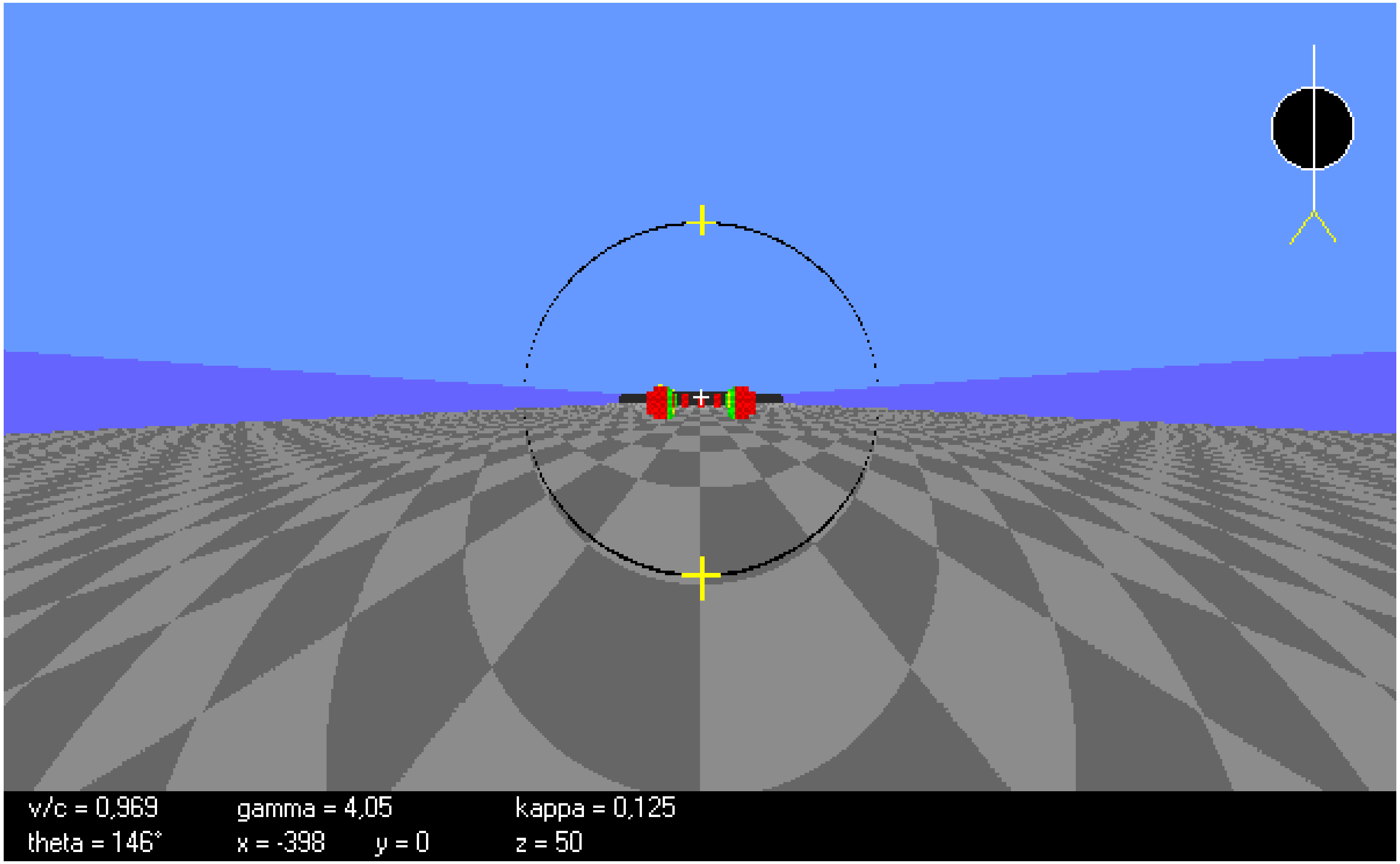
Bright tram



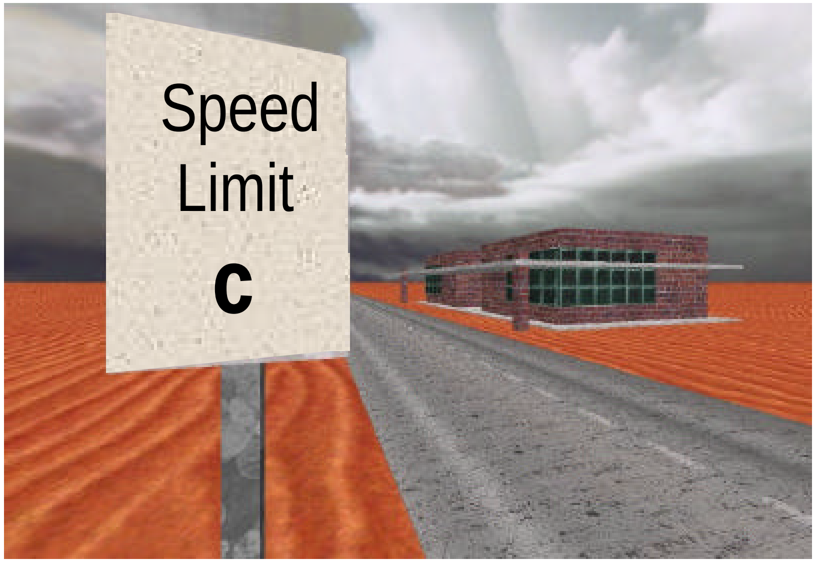







v/c = 0,969
gamma = 4,05
kappa = 0,125
theta = 146°
x = -398
y = 0
z = 50

Relativistic aberration



Here we are on a remote (desert) highway, where the speed limit is the speed of light

Now we are moving at about 3/4 the speed of light. Note relativistic aberration!

Doppler shift and headlight effect

Now we turn on Doppler shifting, so that the desert and the sky are blueshifted ahead

Now we turn on the "headlight" effect. Light is concentrated in the direction of motion, which seems brighter, while everything around appears dimmer.

This is probably what a proton "sees" - just a bright spot ahead!

Special relativity paradoxes

- There are numerous so-called "paradoxes" associated with special relativity. They are apparent contradictions, arising because of stubborn clinging to Galileo's notions of unique time and space existing in a single moment in time.

- One of the most famous paradoxes is the twin paradox. Let us consider it in detail. It will also help us understand how to use space-time diagrams.

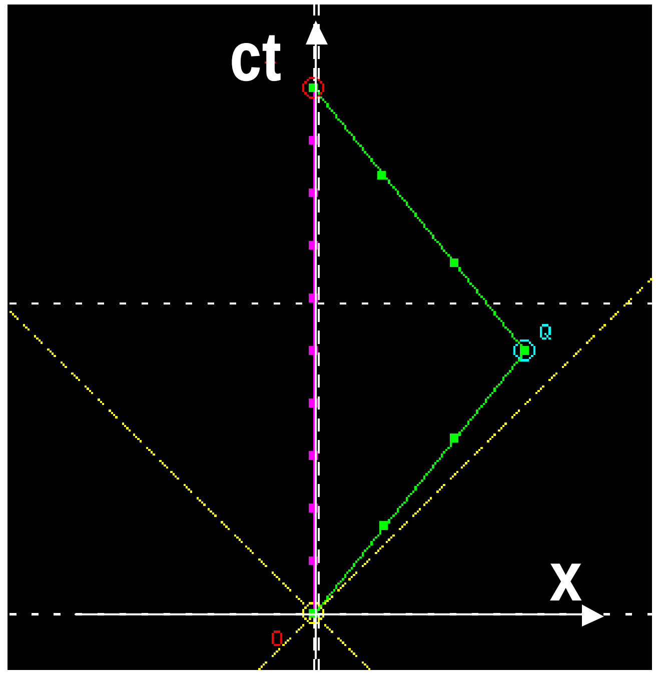
The twin "paradox"

On their 16th birthday, Jane gets her space ship driver's license and takes off from Earth at 0.8 *c*. Her twin brother Joe stays home.

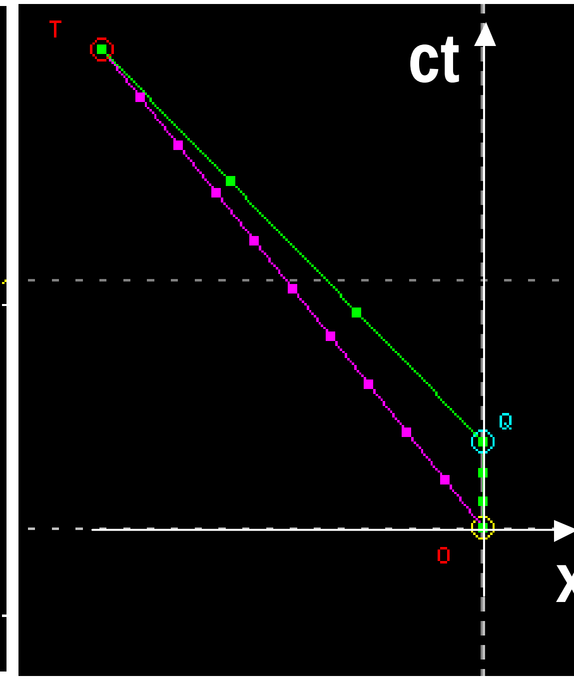
Jane is gone for 6 yrs her time, and Joe gets older by $6/\sqrt{1-(0.8c/c)^2}$ = 10 yrs

The "paradox" lies in the fact that from Jane's point of view, it was *Joe* who traveled. Shouldn't *he* be younger, then?

Joe's frame



Jane's frame



Jane has TWO inertial reference frames!

How does kinematics cope with relativity?

- It's all very well to say that nothing can move faster than light, but Newtonian mechanics says that:

$$\vec{F} = m\vec{a} \equiv m\frac{\Delta\vec{v}}{\Delta t}$$

- So if we apply more and more force to an object, we can increase its speed more and more, and nothing tells us that it can't move faster than light!
- This means that Newton's second law must be modified in relativity. It becomes:

$$\vec{F} = \frac{\Delta(m\vec{v})}{\Delta t}$$

Mass m is no longer constant!

Mass is not preserved anymore!

- It can be shown from first principles (conservation of energy and momentum) and relativity postulates that mass becomes dependent on velocity at large speeds:

$$m = \frac{m_0}{\sqrt{1 - v^2 / c^2}} \Rightarrow$$

m_0 = rest mass

faster means **heavier**!

- If velocity v is very small comparing to c, then this formula becomes

$$m = m_0 (1 - v^2/c^2)^{-1/2} = m_0 \left(1 + \frac{1}{2}\frac{v^2}{c^2} + \ldots \right)$$

$$m \approx m_0 + \frac{1}{2} m_0 v^2 \left(\frac{1}{c^2} \right) \Rightarrow \Delta m = \frac{\Delta(\text{kin.energy})}{c^2}$$

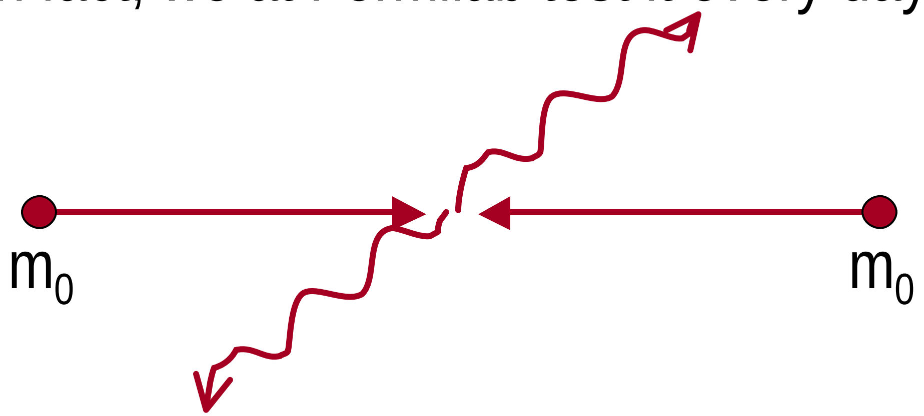
kinetic energy

- Such considerations led Einstein to say that the mass of an object is equal to the total energy content divided by c^2

The world's most famous equation

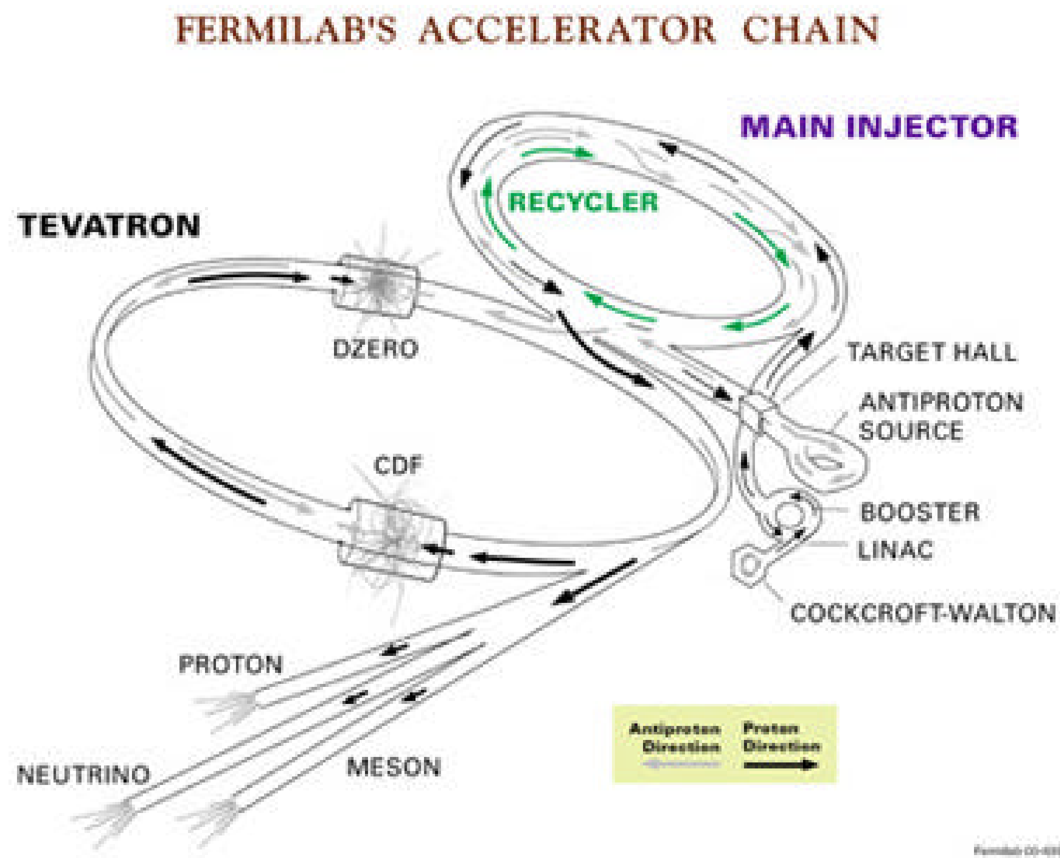
$$E = mc^2 \equiv \frac{m_0 c^2}{\sqrt{1 - v^2 / c^2}}$$

- The equivalence of energy and mass has been confirmed by numerous experiments -- in fact, we at Fermilab test it every day!



An electron and an anti-electron (positron) of mass m_0 collide and annihilate, and two photons, each with energy = m_0c^2, come out!

Fermilab's accelerators



Relativity and anti-matter

- Given the relativistic equations for energy, mass, and momentum, we can obtain the following relation:

$$\boxed{E^2 - \vec{p}^{\,2} = m_0^2}$$

- Note that this means that E has two solutions, one with plus and one with minus sign.

- But what does negative energy means? How can anything have negative energy?
- It was this kind of problem that eventually lead people to the idea of anti-matter.

Experimental verifications of special relativity

- Special relativity has been around for almost 100 years, and has brilliantly passed numerous experimental tests
  - Special relativity is a "good" theory in the sense that it makes definite predictions that experimentalists are able to verify.
- Things like time dilation, length contraction, equivalence of mass and energy are no longer exotic words -- they are simple tools that particle physicists use in their calculations every day.
  - Our Tevatron couldn't function a day if we didn't take into account special relativity!
- One should remember that special relativity was not something that Einstein just came up with out of the blue -- it was based on existing experimental results.

Is there anything left of Newton's laws, then?

- Einstein himself felt obliged to apologize to Newton for replacing Newton's system with his own. He wrote in his Autobiographical notes:

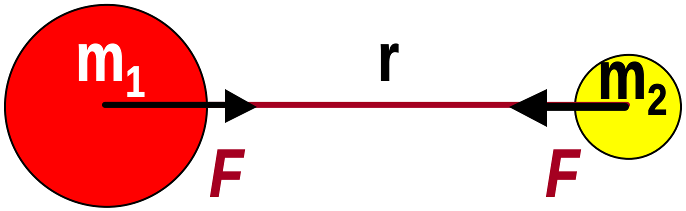
  Newton, forgive me. You found the only way which, in your age, was just about possible for a man of highest thought and creative power.

- However, special relativity does not make Newton's mechanics obsolete. In our slow-moving (comparing to the speed of light) world, Newton's mechanics is a perfect approximation to work with.

What is general relativity?

- General relativity is an extension of special relativity to the effects of gravity.
- Why was it necessary?

Newton's law of gravitation



$$F = G\frac{m_1 \cdot m_2}{r^2}$$

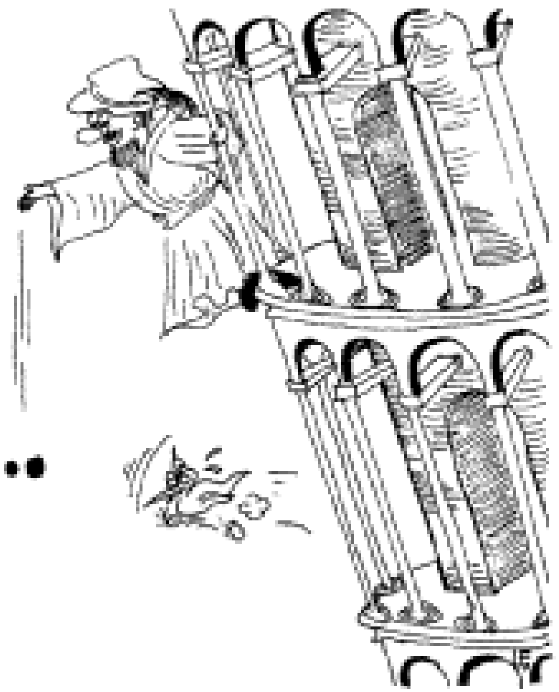
- The universal law of gravity says nothing about **time**
  - If m_1 moved, m_2 would feel the change right away
  - This implies the existence of some agent moving faster than light, which contradicts special relativity

Gravity is special

- We know there are 4 forces of nature:
  - Gravity, Electromagnetism, Weak & Strong Nuclear forces

- Gravity is by far the weakest force,

  but it is also the most obvious

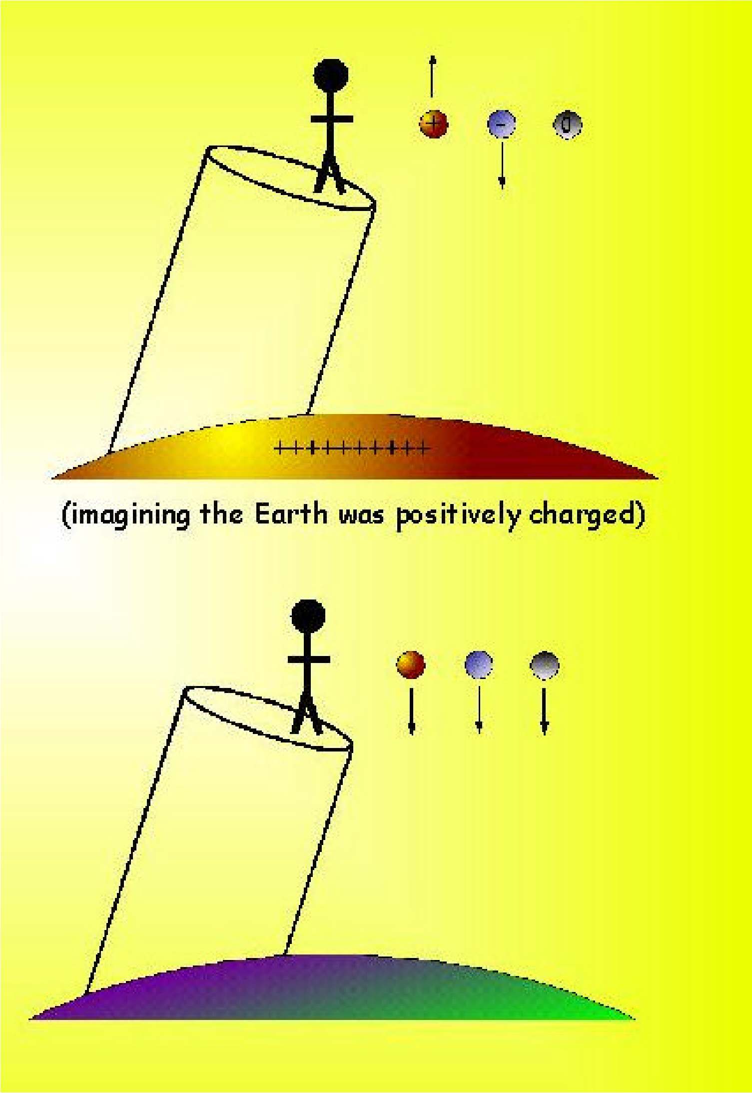


WHY?

  - Because it's **universal**
    - Gravity acts the same on all forms of matter!

Universality of gravity

- Electromagnetism:
  - Particles have different charges (+,-, or 0)
  - Like charges repel, while opposites attract
- Gravitation:
  - All particles react in exactly the same way!



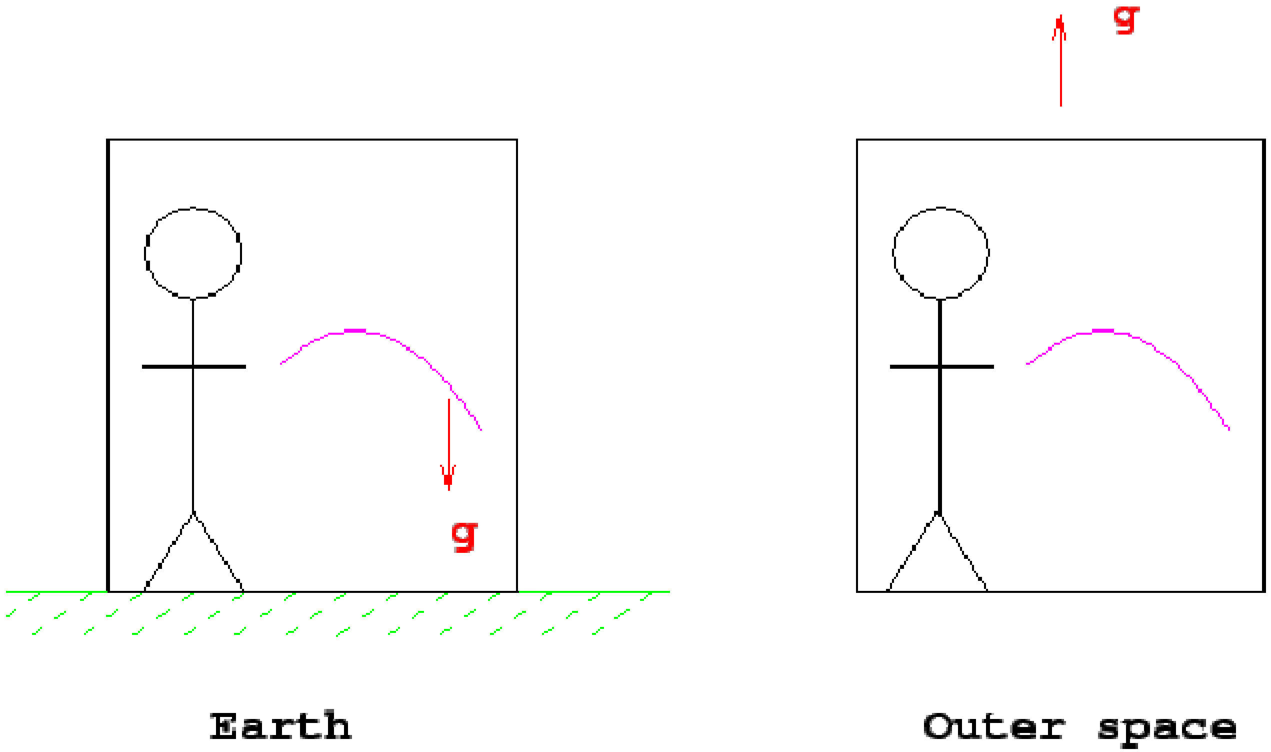
"The happiest thought of my life"

- Einstein developed his General Theory of Relativity with little or no experimental motivation, but driven instead by philosophical questions:
  - What makes inertial frames of reference so special?
  - Why is it that we don't feel gravity's pull when we are freely falling?
  - ...
- The complete formulation of the theory was published in 1916.
- In 1920, Einstein commented that the happiest thought of his life was:

> *The gravitational field has only a relative existence... Because for an observer freely falling from the roof of a house - at least in his immediate surroundings - there exists no gravitational field.*

Equivalence principle

- Einstein realized that if everything feels the same acceleration, that is equivalent to nothing feeling any acceleration at all.

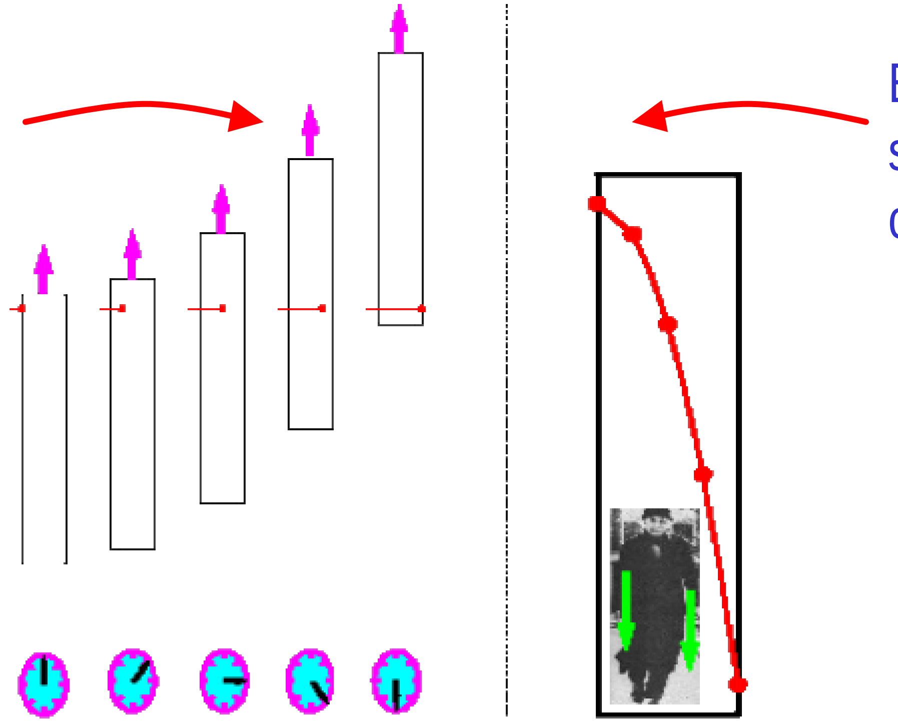


The equivalence principle: an observer inside a (small) enclosed laboratory cannot tell the difference between being at rest on Earth's surface or being accelerated in outer space.

Light bends in a gravitational field!

- A very surprising corollary of the equivalence principle is the fact that light is bent by gravitational forces!
- Consider an elevator being pulled by a crane, so that it moves with a constant acceleration (so its velocity increases uniformly with time)

Crane operator sees the light travel in a straight path

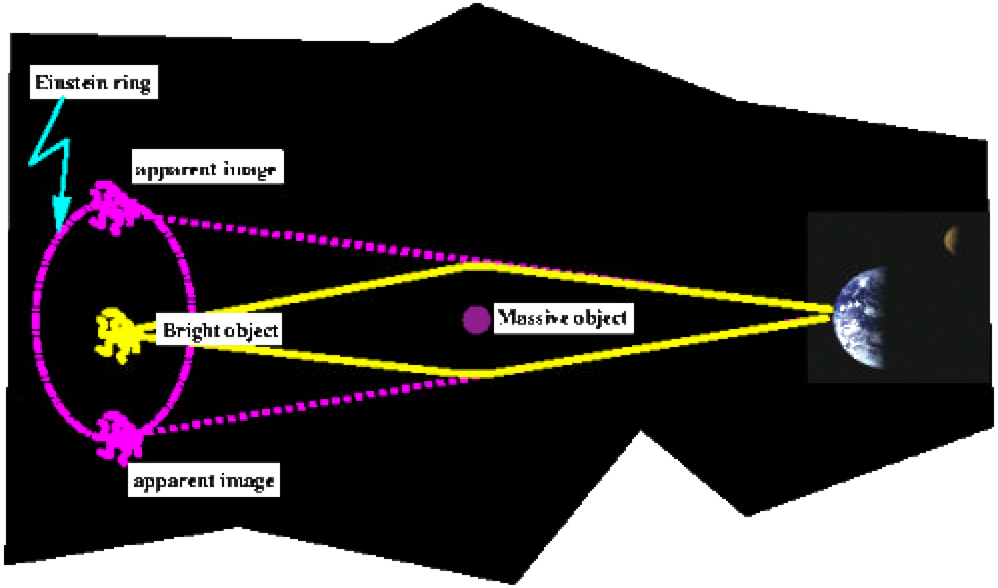


Elevator passenger sees the light path as curved

By the equivalence principle, therefore, light paths are curved by gravity!

Gravitational lensing

- The bending of light by gravity has been observed by astrophysicists.

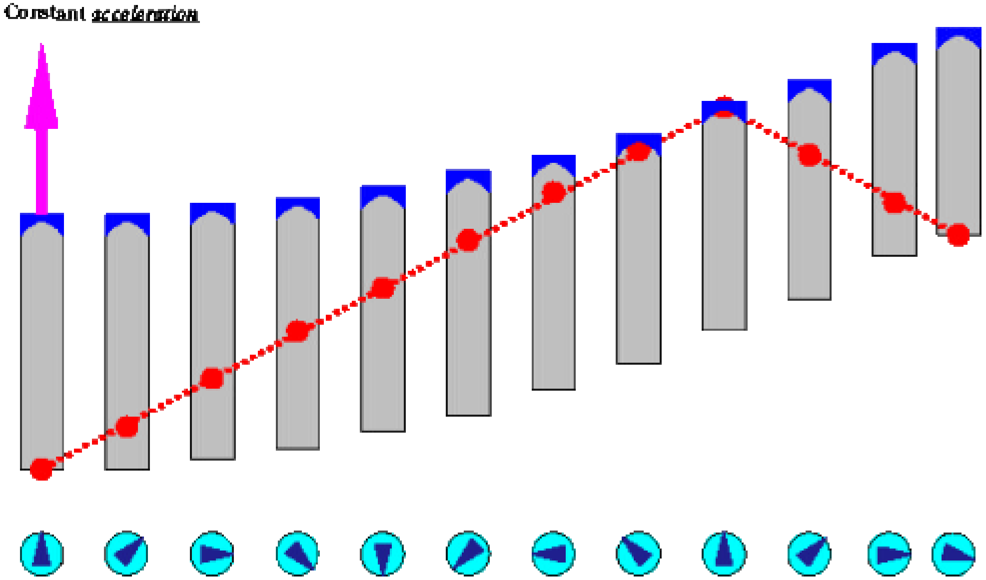


If both the bright object and the massive object are prefect spheres, there will be an apparent image for every point on the ``Einstein ring".

Hubble space telescope image of galaxy cluster CL0024+1654: irregular blue objects are lensed images of a single background galaxy

Time slows down in a gravitational field

- Consider a light clock being accelerated upward, being pulled by a crane



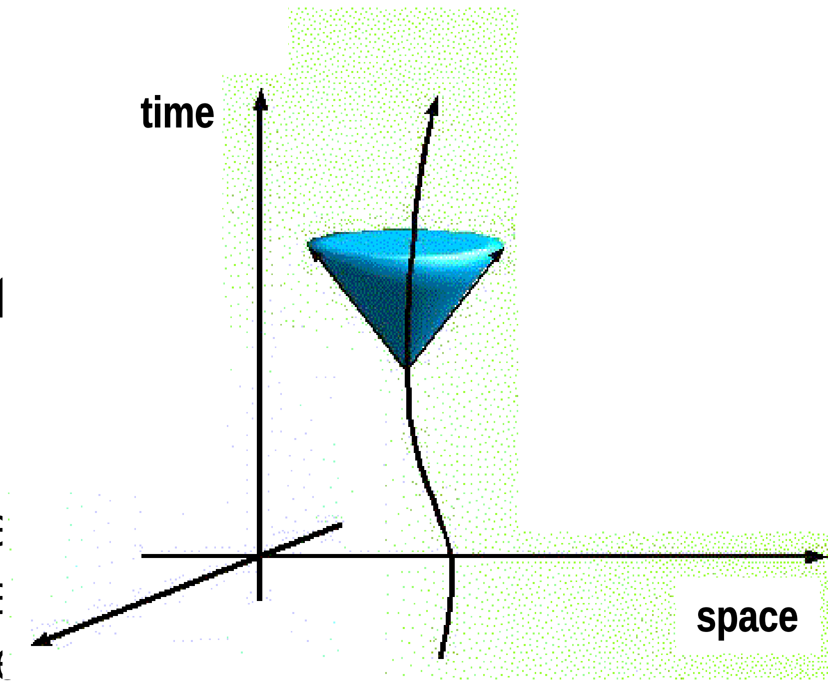
- The circle denotes pulse of light which at the start is sent from a source; after a time it reaches the top of the the box and is reflected.
- The time it takes to do the trip is longer than for a clock at rest!

Space and time

- Consider now a region of empty space relatively near some stars. All objects going into this region will accelerate in precisely the same way.

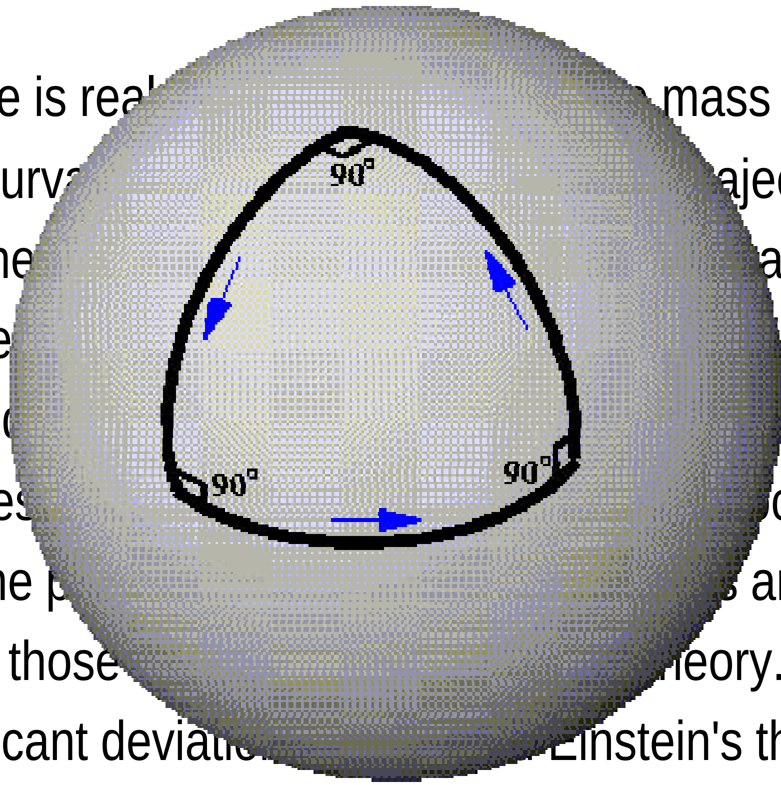
- The conclusion is then that gravity alters the properties of space. It also alters the properties of time (remember the slowing down clock!)

- These changes or deformations of space and time in turn determine the subsequent motion of the bodies in space time: matter tells space-time how to curve and space-time tells matter how to move.



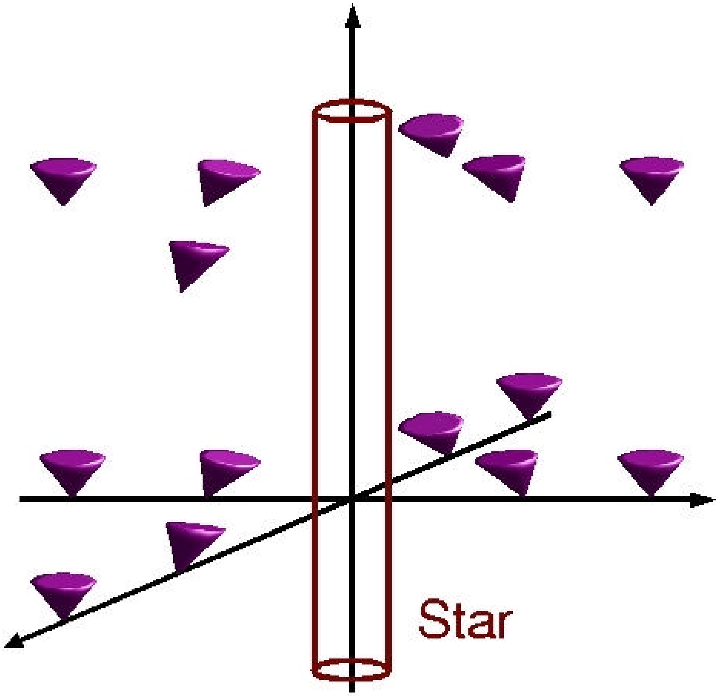
Curvature

- The curvature of space is rea mass of the bodies in it.
- Correspondingly the curv ajectories of all
- bodies moving in it. The atical
- embodiment of this ide tial positions
- and velocities of all bo velocities. In the
- limit where the energies cities are
- significantly below c the p s are
- indistinguishable from those eory. At large speeds
- and/or energies significant deviati Einstein's theory, not
- Newton's, describes the observations.

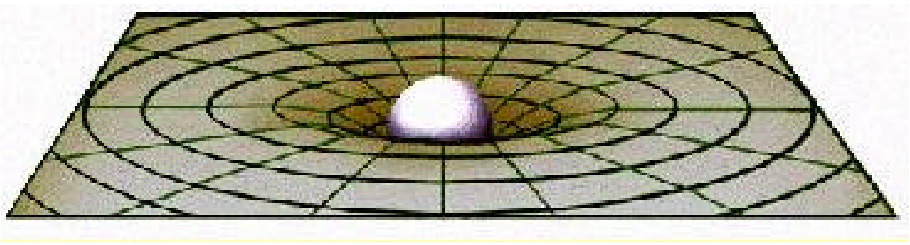


Visualizing spacetime curvature

- We can visualize spacetime curvature by tilting the light cones

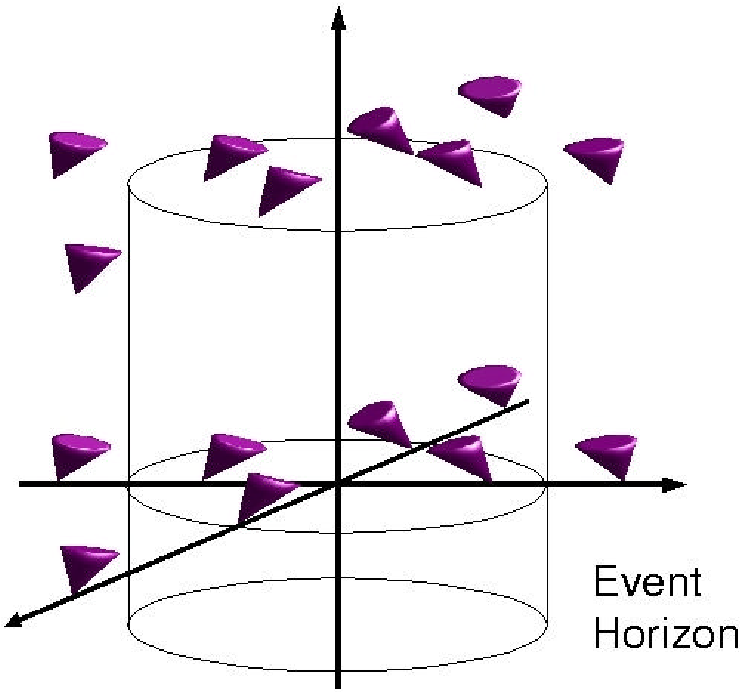


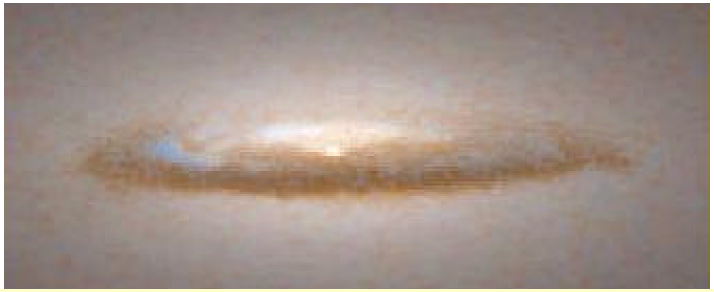
- The warping of spacetime outside a gravitating body deflects trajectories toward the body
  - We interpret that as the **force of gravity**



Black Holes

- If gravity is very strong, light cones tilt so much that all trajectories are forced into a common point (the singularity)
  - That's a **Black Hole**
- Inside the event horizon, falling into the singularity is as inevitable as moving forward in time

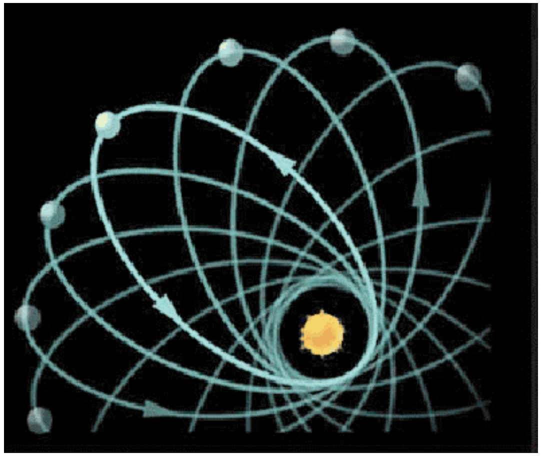


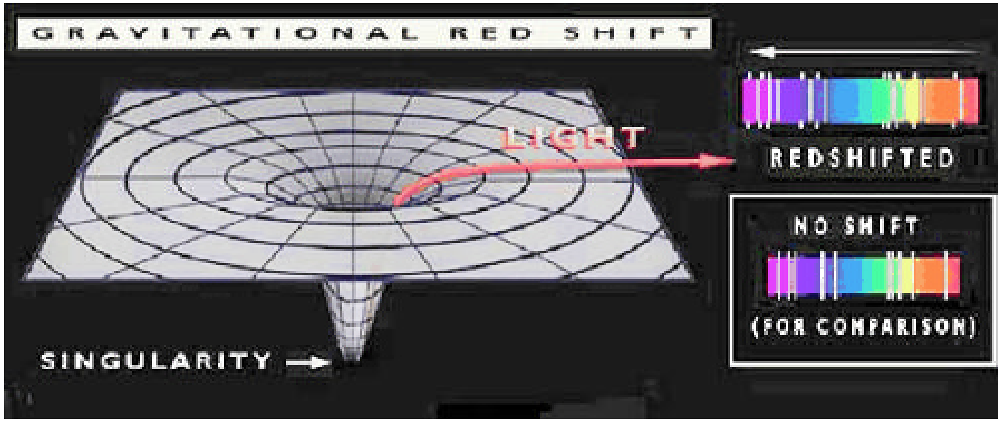


NGC 7052: evidence for a black hole?

Experimental tests of general relativity

- Since 1916, there have been many measurements which agree with general relativity to the available accuracy.
- Some of the "classic" experiments are:
  - Precession of the perihelion of Mercury
    - The orbit of Mercury did not behave as required by Newton's equations
  - Gravitational red-shift
    - light leaving a region where the gravitational force is large will be shifted towards the red
  - Light bending
  - The double pulsar





The relativistic universe

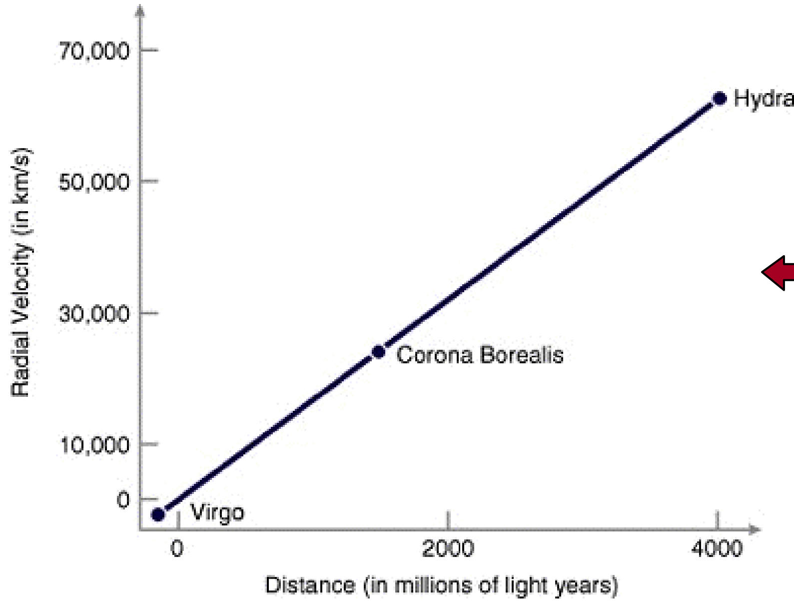
- In everyday life, there are many forces that strongly affect the world around us: friction, electric, magnetic, etc.
- But in the universe at large there is only one predominant force: gravity. It is gravity that determines the structure of the universe at large.
  - This is why we need General Relativity to describe it.

The visible universe is filled with galaxies and is, to first order, homogeneous and isotropic

➔ To Einstein's initial surprise, the universe according to the General Theory of Relativity must expand or contract.

The expanding universe

- Hubble published his famous observations that demonstrated that our universe is, in fact, expanding.
  - the manner in which it expands agrees with the predictions of the solutions first obtained by Einstein.



<u>Hubble law</u>

The speed at which galaxies are receding from the Milky Way is proportional to their distance from it

According to General Relativity the universe is expanding, but this does not mean that the galaxies and such are flying out into space, it means that **space itself is growing**, and in so doing, it increases the separation between the galaxies.

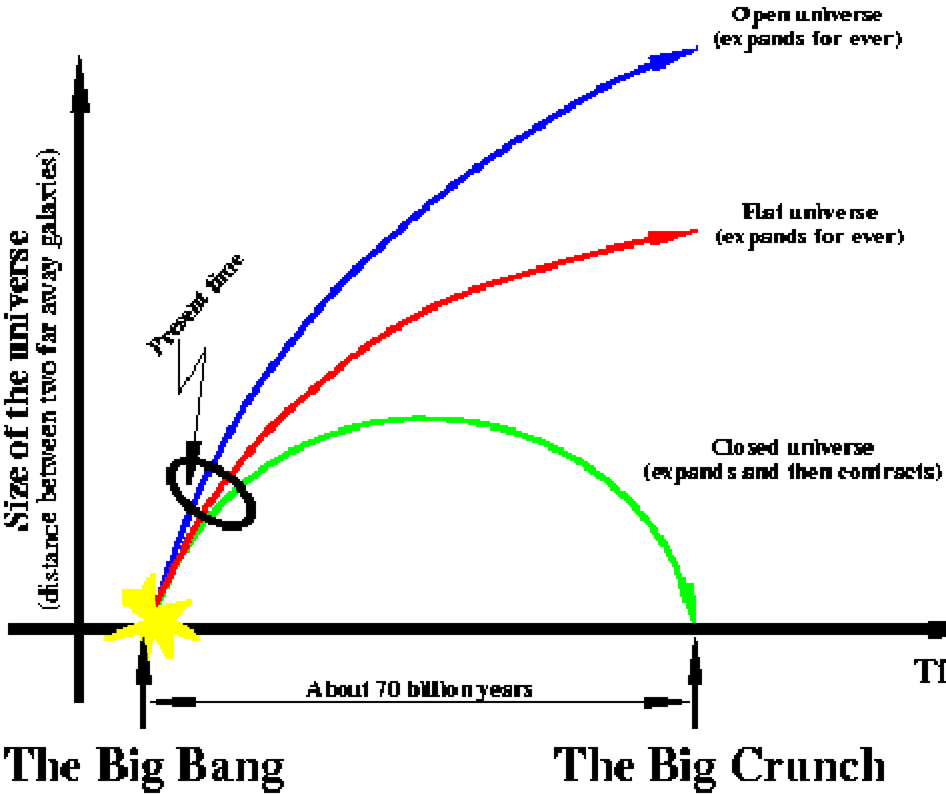
And now what?

The universe expanding, but what will become of it?

There are three possible solutions to the equations of the General Theory of Relativity which represent homogeneous and isotropic universes:

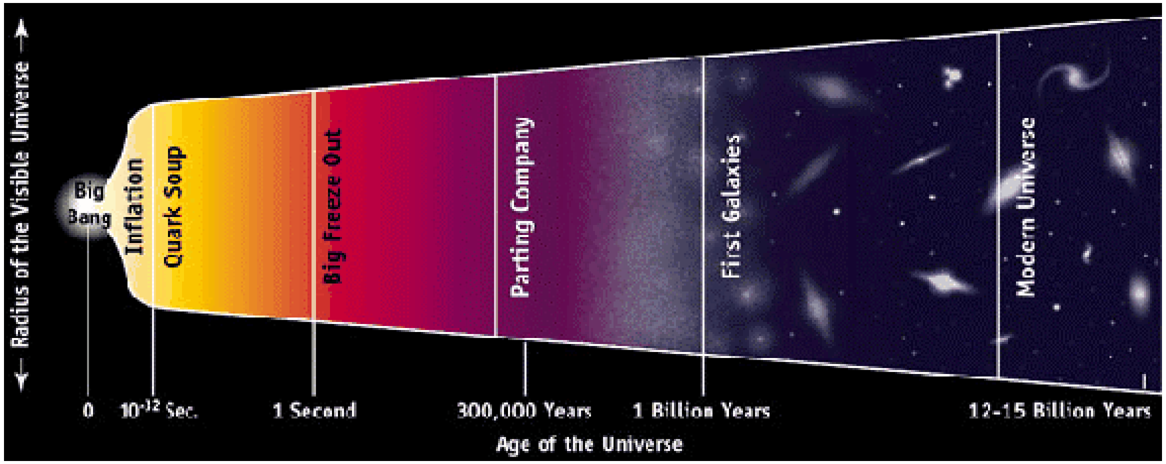
1. it will continue its expansion forever,
2. it will eventually stop and re-contract
3. it will expand slowing down to a stop at infinite time.

Of these possibilities the one corresponding to our universe is determined by the amount of matter in the cosmos.



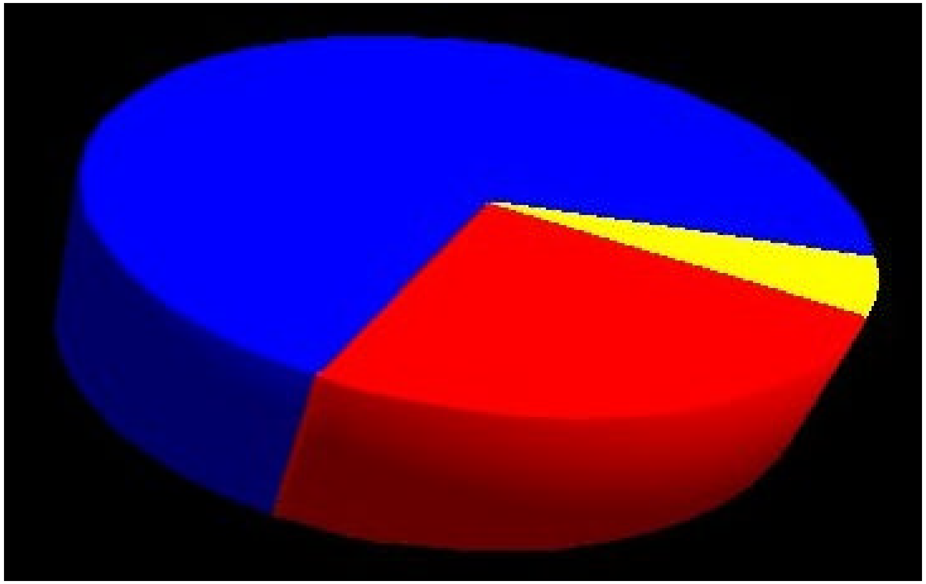
So how much matter is there in the universe?

- We don't really know
  - When considering the universe we observe only what we can see.
  - Nonetheless there are strong indications that there is something more (dark matter)
    - This is the cutting edge of modern-day experimental cosmology
- The latest results suggest that the universe will expand forever, but at present its ultimate fate is unknown.



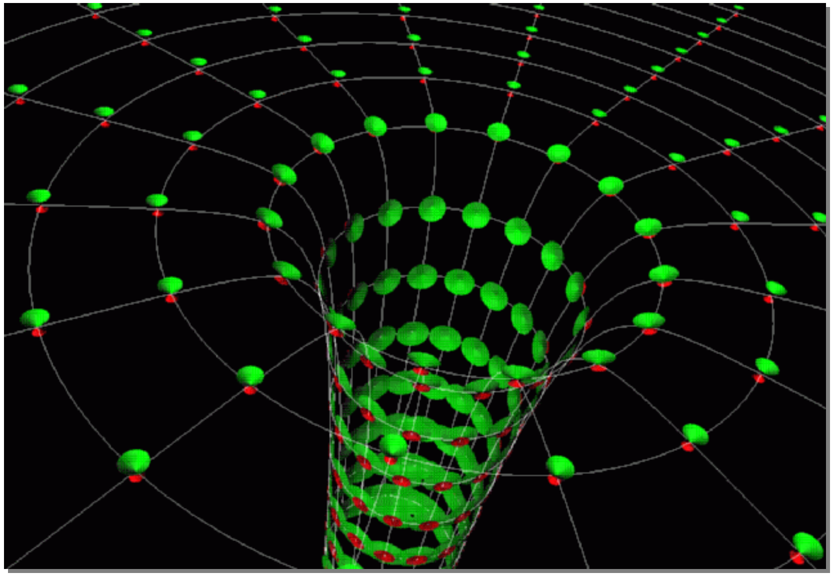
Dark energy?!

- This leaves 95% of the universe as stuff which is completely invisible. As depicted, it comes in two components: 25% "dark matter" (in red) and 70% "dark energy" (in blue). The difference between the two is in how they behave: dark matter acts like ordinary particles, in that it collects into dense regions (like galaxies or clusters of galaxies), whereas dark energy is smoothly distributed throughout space and slowly-varying in time. The best candidate for dark energy is the cosmological constant, or "vacuum energy": the idea that there is a nonzero amount of energy density inherent in the fabric of spacetime itself.



Reconciling gravity with the other forces

- The (well-) known Universe consists of:
  - "Matter": electrons, protons, neutrons, you
  - "Forces": electromagnetism, weak & strong nuclear forces, gravity
- A crucial distinction:
  - Matter and non-gravitational forces move through spacetime
  - Gravity, however, IS spacetime!

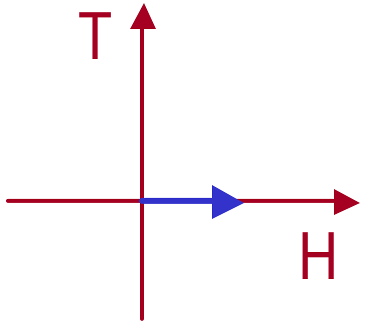


Incompatibility with Quantum Mechanics

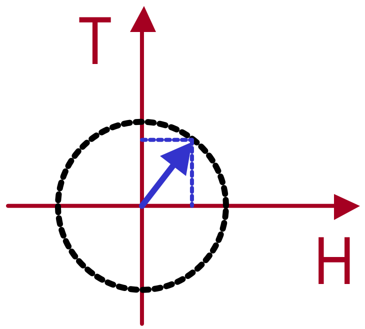
- This distinction becomes a full-blown incompatibility when we take into account the theory underlying all of modern physics:

Quantum Mechanics

  - You had a lecture on QM at the beginning of November



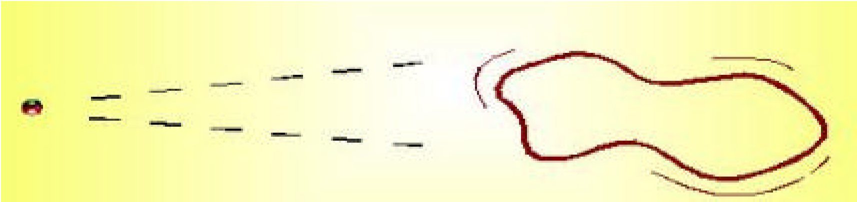
- Quantum mechanics in a nutshell: flipping a coin
  - An ordinary ("classical") coin is always heads or tails, even if we don't know which



  - A quantum-mechanical coin is described by a vector (an arrow) in the heads/tails plane. When we observe the coin, we only ever see heads or tails. The arrow tells us the probability of observing H or T.

Possible solution in sight?

- A promising strategy in such a situation is to invent a completely new theory, which is both consistent with quantum mechanics and somehow includes gravity
- Leading candidate at the moment: string theory



Basic idea: if you look closely enough at any elementary particle, it's really a vibrating loop of "string"!

- This seems to solve some technical, but not conceptual, problems.
- This brings up to the cutting edge of modern physics
  - One day one of you may come up with a consistent theory of quantum gravity!

String theory pros and cons

- Pros:
  - An apparently consistent quantum theory of gravity
  - A new understanding of what happens to things that fall into black holes -- not all information is lost forever
- Cons:
  - Spacetime has to have more than four dimensions
    - Maybe 10, maybe 11 -- the extra ones must be hidden somehow
  - We don't understand the theory completely
    - Hard to say anything with confidence
  - Hard to make testable predictions (but people do try!)

Conclusions

- Special relativity revolutionized our understanding of space and time
  - There is no "space" and "time" by themselves -- there is only four-dimensional space-time!
- It describes the motion of particles close to the speed of light
  - No massive particles can ever exceed the speed of light
  - Massless particles move at the speed of light
- Special relativity has been extremely well-tested by experiment.
- At everyday speeds, Newton's mechanics is a good approximation to work with.
- General relativity is an extension of special relativity to the effects of gravity
  - Reconciling gravity with quantum mechanics is one of the major goals and dreams of modern theoretical physicists

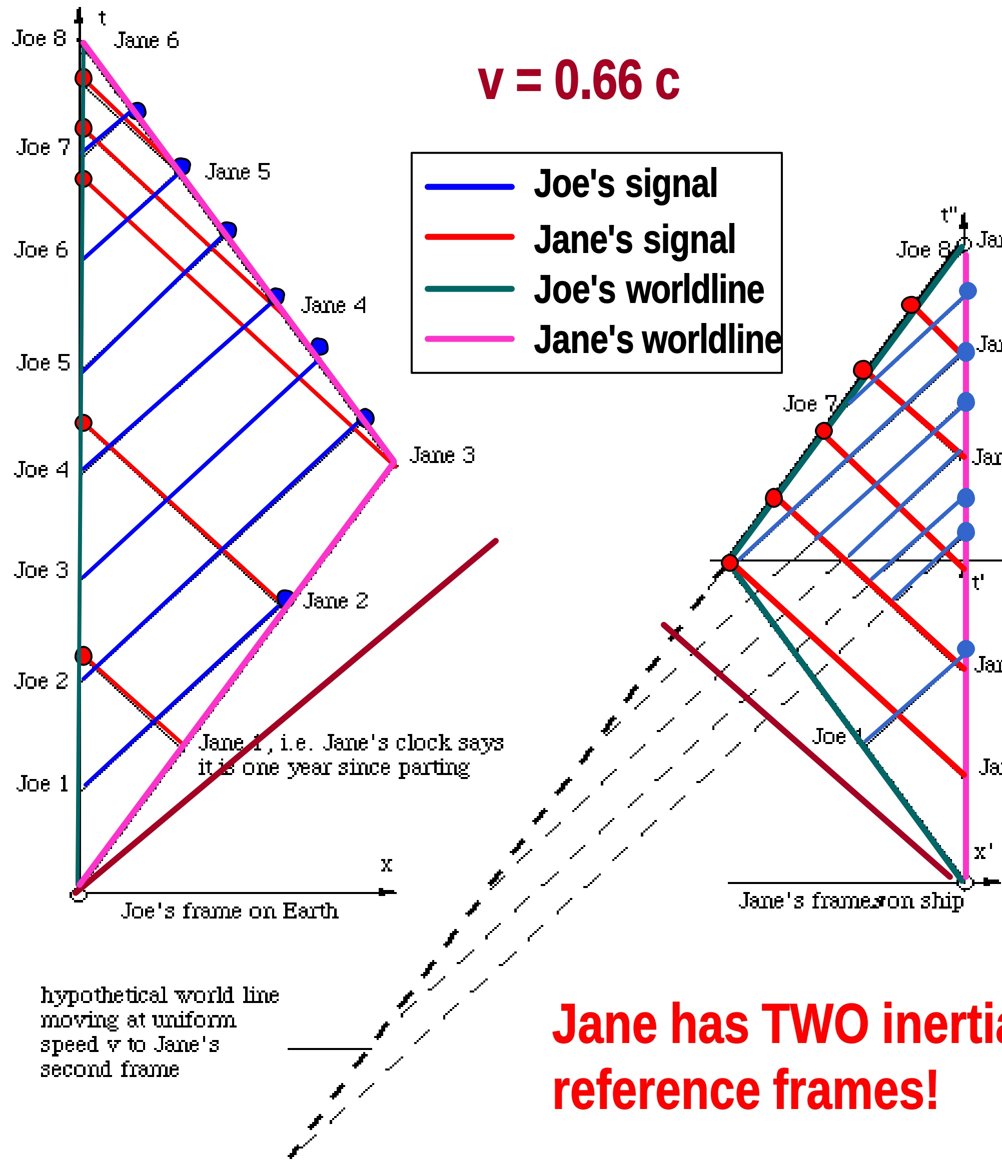
For further reading

- A. Einstein ***Relativity*** (Three Rivers Press, 1961)
- H. Bondi ***Relativity and Common Sense*** (Dover, 1962)
- R.P. Geroch ***General Relativity from A to B*** (University of Chicago Press, 1978)
- R. Penrose ***The Emperor's New Mind*** (Oxford University Press, 1989)
- J. Schwinger ***Einstein's Legacy*** (Scientific American Library, 1986)
- J.L. Synge ***Talking About Relativity*** (North-Holland, 1970)
- K.S. Thorne ***Black Holes and Time Wraps*** (W. W. Norton, New York, 1994)
- E. F. Taylor and J. A. Wheeler ***Spacetime Physics*** (W.H. Freeman, New York, 1966) -- this one is a little more technical!

- **Please contact me if you have any questions: nataliak@fnal.gov**

The twin "paradox"

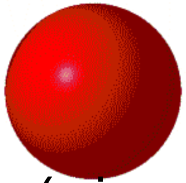
- On their 16th birthday, Jane gets her space ship driver's license and takes off from Earth at 0.66c. Her twin brother Joe stays home.
- Jane is traveling towards a distant star, located 2.67 light years away from Earth in Joe's frame, and back.
- By how much will Joe and Jane have aged when they meet?
- **Joe: 2.67 * 2 / (0.66c) = 8 yrs**
- **Jane: 2.67 * $\sqrt{1-(0.66c/c)^2}$ / (0.66c) = 6 yrs**
- The "paradox" lies in the fact that from Jane's point of view, it was *Joe* who traveled. Shouldn't *he* be younger, then?



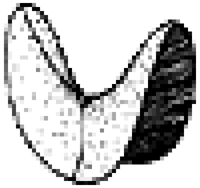
Jane has TWO inertial reference frames!

A comment on geometry…

- It is hard for us to think of going from one inertial system to another as a hyperbolic rotation. Partly this is because we are not used to thinking in terms of pseudo-Euclidean geometry.
- The familiar three-dimensional world around us is **Euclidean**, so it's very natural for us to imagine circles and spheres that do not change under rotations ($x^2 + y^2$ stays the same)



- But space-time is ***pseudo*-Euclidean** (minus instead of plus in what stays the same under rotations).



- Thus, Einstein's special theory of relativity is not about how "everything is relative" -- it's about the deepest connection between space and time, and the nature of space-time.
  - Our understanding of space and time was further revolutionized in General Relativity…